UNIVERSIDADE TECNOLÓGICA FEDERAL DO PARANÁ
PROGRAMA DE PÓS-GRADUAÇÃO EM ENGENHARIA MECÂNICA E DE MATERIAIS

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PROJETO DE REDES DE FORNECIMENTO REGENERATIVAS

TESE

CURITIBA

2019

VITOR MIRANDA DE SOUZA

PROJETO DE REDES DE FORNECIMENTO REGENERATIVAS

Tese apresentada ao Programa de Pós-graduação em Engenharia Mecânica e de Materiais da Universidade Tecnológica Federal do Paraná como requisito parcial para obtenção do grau de "Doutor em Engenharia" – Área de Concentração: Engenharia de Manufatura.

Orientador: Milton Borsato

Co-orientadora: Jacqueline Bloemhof-Ruwaard

CURITIBA

2019

Dados Internacionais de Catalogação na Publicação

S729d Souza, Vitor Miranda de
2019 Design of regenerative supply networks / Vitor Miranda de Souza.-- 2019.

Disponível via World Wide Web
Texto em inglês com resumo em português
Dissertação (Mestrado) - Universidade Tecnológica Federal do Paraná. Programa de Pós-graduação em Engenharia Mecânica e de Materiais, Curitiba, 2019
Bibliografia: p. 139-164

1. Engenharia mecânica - Dissertações. 2. Resiliência (Ecologia). 3. Transdisciplinaridade. 4. Programação linear. 5. Sistemas dinâmicos. I. Borsato, Milton, orient. II. Bloemhof-Ruwaard, Jacqueline, coorient. III. Universidade Tecnológica Federal do Paraná - Programa de Pós-Graduação em Engenharia Mecânica e de Materiais, inst. IV. Título.

CDD: 620.1

Biblioteca Ecoville da UTFPR, Câmpus Curitiba
Lucia Ferreira Littiere – CRB 9/1271

TERMO DE APROVAÇÃO DE TESE Nº 19

A Tese de Doutorado intitulada: **DESIGN OF REGENERATIVE SUPPLY NETWORKS**, defendida em sessão pública pelo Candidato **Vitor Miranda de Souza**, no dia 20 de fevereiro de 2019, foi julgada para a obtenção do título de Doutor em Engenharia, área de concentração: Engenharia de Manufatura, e aprovada em sua forma final, pelo Programa de Pós-Graduação em Engenharia Mecânica e de Materiais – PPGEM.

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A via original deste documento encontra-se arquivada na Secretaria do Programa, contendo a assinatura da Coordenação após a entrega da versão corrigida do trabalho.

Curitiba, _____de _______________de 20___.

Carimbo e assinatura do Coordenador do Programa

____

ACKNOWLEDGEMENTS

What a journey! There is just too many people I wish to pay tribute. First of all, I want to say a warm thanks to my beloved wife, Paula, who was always there for me whenever we were together or apart - I could not have done this without her. To my family: my mother Marta and father Ivan, who taught me the ways of engineering design and teaching. My brothers Cesar and Mauro, who I had the honour and the pleasure to share so many stages through almost twenty years with you, performing good music. To my angels in the sky: Paivô, Licy and Ana Luísa. Love you all very much.

Second, to my dear advisors Prof. Borsato and Prof. Bloemhof, for believing in me and pushing me through challenges I could never imagine I could overcome. I hope I can express the gratitude I have for everything I learn from you.

Thank you dear fellow Professors from the Academic Department of Mechanical Engineering of the Federal University of Technology - Parana, campus Cornélio Procópio. Your warm friendship and support made me realise I belong in a special place. I'm looking forward to come back and give back everything I was gifted with. To the PPGEM staff, and CAPES, who provided with the funding and making sure I received it.

To those who helped in the search for a true problem to investigate: Evanio, Marcelo, Ariane e Rafael Costa from FIEP and Paulo Figura and João from IPCC, which were very helpful whenever I needed. To my office mates in LAMIS: Juliana, Sérgio, Kaio, Gisele, Sato, Rafael, Ana and Jaqueline.

Thank you Prof. Dr. Nel Wognum who linked us the Wageningen University and Research (WUR) and Prof. Dr. Alfons Oude Lansink, which in turn linked us with the Operations Research and Logistics group. Initially, we were looking to establish a connection with the TU Delft, and did not even hear about WUR. In the end, I could not have asked for a better place to spend one year abroad.

To all the people that I met during this one year in The Netherlands. From the room 6029 of the Operations Research and Logistics group in WUR: Alistair, Heleen, Jochem - guys, thank you for all the friendship you have given me. To the people in the neighbour offices: Joke and Argyris, Marjolein, Ante, René, Viet, Sonja, Ismail, Claudia, Natasja, Renzo, Dimitri, Karin, Frits, Eligius, Behzad, Helen, Xhu. To the INF group people: Geert Jan, Ayalew, Ioannis,

Bedir, Floor, Giulia, Sjoukje, Marteen and Mark. It was an honour and a pleasure to spend time with you.

To my dear roommates in Beringhem, which transformed what was to be a lonely period into moments I'll never forget: Matej, Katerina, Pavlos, Elke, Guido, Sergio, Sotiris, Elena, Peter, Samuel, Farkhan, Essam, Pong, Lise, Sara, Francesco, Juan Luis, Jorge, Damian and Alan, Patrick, Leonardo, Nour, Joana - the only Brazilian I managed to properly meet -, Stelios, Stefano and Penny (who helped me when I was sick), Emma, Alejandra, Daniel, Li. My Friday nights will never be the same: if only those kitchen walls could speak...! To the Beringhem visitors, so glad when you came along! Alberto, Laszlo, Nachito Juan Ignacio, Angelos, Nico, Michelle(s). All those potlucks...

Finally, thanks to all the reviewers of the articles submitted, for their fundamental feedback.

Thank you so very much. You will be in my heart, forever.

RESUMO

DE SOUZA, Vitor Miranda. PROJETO DE REDES DE FORNECIMENTO REGENERATIVAS. 198 f. Tese – Programa de Pós-graduação em Engenharia Mecânica e de Materiais, Universidade Tecnológica Federal do Paraná. Curitiba, 2019.

A estratégia de minimização de impactos ambientais não tem sido efetiva suficiente para reverter os danos causados ao meio ambiente por sistemas de produção. É necessário ir além, maximizando os benefícios e engajando-se ativamente na regeneração de ecossistemas degradados. Estes sistemas de produção também devem ser capazes de se adaptar a distúrbios, garantindo o cumprimento da sua função - habilidade denominada de Resiliência - e a manutenção destes benefícios ambientais no longo prazo. Iniciativas voltadas para o projeto de redes de fornecimento - um tipo específico de sistemas de produção - tem focado em melhorar sua eco-eficiência, propor definições mais eco-efetivas para estas redes, ou melhorar sua Resiliência. No entanto, nenhuma iniciativa que conjugue estas três abordagens, com enfoque em regeneração ambiental, pode ser encontrada na literatura. Esta tese tem como objetivo contribuir nesta direção, propondo um procedimento para a realização de projeto de redes de fornecimento que promovam a regeneração do meio ambiente enquanto cumprem sua função operacional. Este procedimento foi elaborado utilizando a metodologia de *Design Science Research* (DSRM). O progresso científico do Projeto Sustentável no contexto da Gestão de Operações foi mapeado em uma revisão de literatura realizada utilizando-se a metodologia *ProKnow-C*. A Rede de Fornecimento Regenerativa é caracterizada, e o processo de Projeto de Redes de Fornecimento Regenerativas (PRFR) é definido a partir dos conceitos de Redes de Fornecimento Sustentáveis, Projeto de Cadeias de Fornecimento, Abordagem Sistêmica e Projeto Regenerativo. O procedimento PRFR é definido em quatro etapas: (i) descrever os entornos da rede e identificar um propósito regenerativo; (ii) reprojetar as saídas, entradas e processos de transformação; (iii) executar o projeto conceitual do sistema, onde as interações são decompostas, e princípios de resiliência são adotados. No quarto estágio, o desempenho da rede é otimizado, e a resiliência é quantificada e verificada por meio do *Ecosystem Network Analysis*. O procedimento PRFR é utilizado para projetar uma rede de gestão de resíduos domésticos, cuja função de dar disposição aos resíduos é cumprida, enquanto o meio ambiente é regenerado. O propósito de regeneração é identificado após escrutínio da região do Norte Pioneiro, Paraná. Vinte e três áreas degradadas por descarte inadequado de resíduos foram identificadas; o propósito regenerativo da rede é recuperar estas áreas. Entradas são identificadas e saídas redefinidas, de acordo com os processos de recuperação: seleção, compostagem aeróbica, digestão anaeróbica e gaseificação. Um modelo de sistema dinâmico que prevê o volume de resíduos gerados, descartados e coletados para um período de vinte e um anos (2018-2038) e um modelo de programação linear multi-cenário, multi-período, multi-objetivo, inteira mista (MC-MP-MO-PLIM) foram desenvolvidos, produzindo configurações para a rede por meio da maximização do lucro e da economia líquida na emissão de gases de efeito estufa. Os desempenhos econômico, ambiental e social das soluções obtidas para os quatro cenários são apresentados e discutidos. A principal contribuição desta pesquisa é demonstrar o potencial que redes de fornecimento possuem de regenerar ecossistemas no longo prazo, apresentando um desempenho sustentável nas dimensões econômica, ambiental e social. Limitações e pesquisas futuras também são apresentadas.

Palavras-chave: Projeto regenerativo, Resiliência, Redes de Fornecimento, Ecocentrismo, Transdisciplinaridade, Programacão Linear Inteira, Sistemas Dinâmicos.

ABSTRACT

DE SOUZA, Vitor Miranda. DESIGN OF REGENERATIVE SUPPLY NETWORKS. 198 f. Tese – Programa de Pós-graduação em Engenharia Mecânica e de Materiais, Universidade Tecnológica Federal do Paraná. Curitiba, 2019.

The strategy of environmental impact minimisation has not been effective enough to revert the damage caused to the environment by production systems; a shift is needed towards promoting environmental benefits. These production systems must also cope with disturbances, while ensuring that their function is fulfilled - a capability known as Resilience - to deploy environmental benefits in the long term. Initiatives in the field of Supply Network Design - a specific type of production system - have focused on improving eco-efficiency, proposing eco-effective networks, or enhancing their Resilience. However, it could not be found in the literature any initiative that merge these three approaches, with a focus on environmental regeneration. This thesis aims to contribute in this direction, proposing a procedure to design supply networks that regenerate the environment as it simultaneously fulfil its function. This procedure is approached as an artefact, and Design Science Research Methodology (DSRM) is used for its development. The scientific progress of Sustainable Design (SD) in the context of Operations Management (OM) is mapped through a holistic literature review, based in the ProKnow-C - a methodology to perform bibliometrics and systemic analysis. The Regenerative Supply Network is characterised through the concepts of transdisciplinarity, eco-effectiveness, eco-efficiency and resilience. A definition for the RSND process is proposed, and the RSND procedure is designed, consisting of four stages: (i) description of the network surroundings and identification of a regenerative purpose; (ii) redesign of outputs, inputs and transformation processes; (iii) system conceptualisation, where interactions are depicted using the Socio-Technical and the Socio-Ecological System views, and resilience principles are addressed. (iv), the network environmental and economic performance are optimised, and resilience is quantitatively checked using the Ecosystem Network Analysis. The activities of Demonstration and Evaluation are described in Chapter Four, where the RSND procedure is used to design a household waste management network which regenerates the environment. The regenerative purpose was identified after scrutiny of the Norte Pioneiro region. Twenty-three sites degraded from improper waste disposal were identified; the primary purpose of the waste management network is to regenerate these sites into solar farms, recreational parks or reforested areas. Inputs are identified and outputs are redefined, according to waste recovery options of recyclables sorting, aerobic composting, anaerobic digestion and gasification. Two models were developed: first, a system dynamics model to forecast waste generation, disposal and collection for a 21-year period (2018-2038). Second, a Multi-Scenario, Multi-Period, Multi-Objective, Mixed Integer Linear Programming (MS-MP-MO-MILP) model was developed to solve the capacitated facility location-allocation problem, producing network configurations through two optimisation strategies: maximisation of profit and maximisation of net greenhouse gas (GHG) savings. Economic, environmental and social performance of the solutions obtained for each of the four scenarios are presented and discussed. The main contribution of this research is to show the potential of supply networks to contribute with the regeneration of ecosystems in the long term, with a sustainable performance in the three dimensions. Limitations and future research are also presented.

Keywords: Regenerative Design, Resilience, Supply Networks, Ecocentrism, Transdisciplinarity, Mixed-Integer Linear Programming, System Dynamics.

LIST OF FIGURES

FIGURE 1 – Thesis Overview 21
FIGURE 2 – Review Procedure 24
FIGURE 3 – Dimensions and Keywords 25
FIGURE 4 – Retrieved articles per database 26
FIGURE 5 – Articles organised by year of publication, per search engine 27
FIGURE 6 – Mindmap of subject areas and categories 31
FIGURE 7 – A framework for understanding the roles of government policy and innovation 32
FIGURE 8 – Structural model – indirect/mediating effects 34
FIGURE 9 – NIST Indicator Categorisation Structure 35
FIGURE 10 – Exergy flows on earth represented with emergese 38
FIGURE 11 – Product life spans and sustainable consumption 42
FIGURE 12 – Hypothesis testing for green marketing 44
FIGURE 13 – Evolution of sustainable manufacturing 44
FIGURE 14 – Integrated solid waste management 48
FIGURE 15 – Process Diagram of the RSND development process 56
FIGURE 16 – The path towards Regenerative Development 57
FIGURE 17 – The Sustainable Logistics Management Approach 58
FIGURE 18 – A depiction of a Socio-Technical System 60
FIGURE 19 – The Socio-Ecological System Framework 61
FIGURE 20 – Integration between the SES and the STS views 62
FIGURE 21 – The Circular Economy model 63
FIGURE 22 – The Supply Chain and the Supply Network 64
FIGURE 23 – Interpreting systems with ENA 68
FIGURE 24 – Disciplinary and Transdisciplinary Research compared 70
FIGURE 25 – Types of knowledge associated with TR 71
FIGURE 26 – Research Methodology 73
FIGURE 27 – The Regenerative Supply Network Design Procedure 76
FIGURE 28 – Interactions model among the regenerative SN and surrounding SESs 77
FIGURE 29 – Waste destinations and their consequences 86
FIGURE 30 – IMSWM Performance Framework 89
FIGURE 31 – The mesoregion of Norte Pioneiro, Paraná, divided in Regions 6 and 7 . . . 92
FIGURE 32 – Sankey diagram of 2016 MSW destination in Norte Pioneiro, Paraná 92
FIGURE 33 – Land use situation in Norte Pioneiro 94
FIGURE 34 – Organic Waste Recovery Hierarchy 95
FIGURE 35 – System Flow Diagram 97
FIGURE 36 – Stock and Flows diagram of the waste generation dynamics 98
FIGURE 37 – MSW waste collection scenarios 103
FIGURE 38 – Evolution of replacement of plastics by paper, metal and glass 103
FIGURE 39 – Concetual model of the IMWSM network 104
FIGURE 40 – Flowchart to choose the regeneration strategy for each degraded site 106
FIGURE 41 – Optimisation model development sequence 108

FIGURE 42 – Weight distribution for the generation of Pareto Solutions 122
FIGURE 43 – Profit and net GHG savings for all 16 scenarios 123
FIGURE 44 – Location of facilities across the region of Norte Pioneiro, scenario SR 130
FIGURE 45 – Profit performance of Region 6 through time - profit maximisation 130
FIGURE 46 – net GHG savings of Region 6 through time - net GHG maximisation 131
FIGURE 47 – Opening and Closing Facilities through time 132
FIGURE 48 – Endurability variation for Region 6, Scenario SR 133
FIGURE 49 – Pareto frontier of non-dominated solutions for Region 6, scenario SR 134
FIGURE 50 – Synthesis of the Artefacts Designed 142

LIST OF TABLES

TABLE 1 – Top-10 Journals with Impact Factor 28
TABLE 2 – 10-most cited articles 29
TABLE 3 – Evolution of Sustainable Supply Chain Design. 59
TABLE 4 – Vulnerability and Capability Factors of an Enterprises Resilience 66
TABLE 5 – ENA concepts and equations 67
TABLE 6 – The Regenerative Supply Network Outline. 75
TABLE 7 – Advantages and Disadvantages per Waste Recovery Option 88
TABLE 8 – Waste generated *per capita* and fractions by waste type 91
TABLE 9 – Waste recovery options 96
TABLE 10 – Average waste portions considered for the region of Norte Pioneiro 99
TABLE 11 – Fractions by Recyclable Waste Type 100
TABLE 12 – Progression of Strategies and Plastics Replacement through time. 102
TABLE 13 – Composition of Mined Waste. 105
TABLE 14 – Sites grouped by micro region and regeneration strategy. 107
TABLE 16 – Limits for the quantity of opened and closed facilities 121
TABLE 17 – Network features for regions 6 and 7, for net GHG and profit maximisation strategies 126
TABLE 18 – Aggregated results for the region of Norte Pioneiro 128
TABLE 19 – Quantity of regenerated sites per strategy, per year 129
TABLE 20 – Summary of solutions in the Pareto frontier. 134
TABLE 21 – Review of Objectives and Outcomes for each Chapter. 139
TABLE C1 – Municipalities location and population in the Norte Pioneiro 184
TABLE C1 – Municipalities location and population in the Norte Pioneiro (continued) . 185
TABLE C1 – Municipalities location and population in the Norte Pioneiro (continued) . 186
TABLE C2 – Degraded sites in the Norte Pioneiro. 187
TABLE C3 – Facilities CAPEX and GHG “capital” emissions (CAGEM). 189
TABLE C4 – Regenerated sites Parameters. 190
TABLE C4 – Regenerated sites Parameters. (continued) 191
TABLE C5 – Waste processing data of existing RSCs and SLFs. 192
TABLE C5 – Waste processing data of existing RSCs and SLFs. (continued) 193
TABLE C6 – Waste processing parameters. 194
TABLE C7 – Sorting rates for existing RSCs per year, in kg/kg*. 195
TABLE C8 – Evolution of the destination of ashes for each year, in kg/kg. 196

TABLE OF CONTENTS

1 INTRODUCTION 15
1.1 PROBLEM STATEMENT, RESEARCH PURPOSE AND RESEARCH QUESTIONS 18
1.2 RESEARCH OBJECTIVES AND DESIGN 19
1.3 THESIS OVERVIEW 21
1.3.1 Included Publications 21
2 A HOLISTIC REVIEW OF SUSTAINABLE DESIGN IN OPERATIONS MANAGEMENT 23
2.1 REVIEW METHODOLOGY 24
2.2 BIBLIOMETRICS 26
2.3 SYSTEMIC ANALYSIS 30
2.3.1 Management, Monitoring, Policy and Law 30
2.3.2 Strategy and Management 37
2.3.3 Management Science and Operations Research 41
2.3.4 Economics and Econometrics 42
2.3.5 Industrial and Manufacturing Engineering 44
2.3.6 Waste Management and Disposal 46
2.4 DISCUSSION 49
2.5 CONCLUSIONS AND FUTURE RESEARCH 50
3 A PROCEDURE TO DESIGN REGENERATIVE SUPPLY NETWORKS 53
3.1 BACKGROUND 55
3.1.1 Path to Ecocentrism 55
3.1.2 Sustainable Supply Chain Design 58
3.1.3 The Socio-Technical and Socio-Ecological views 60
3.1.4 Circular Economy 62
3.1.5 Supply Chain as a Complex System: the Supply Network 63
3.1.6 Ecosystem Network Analysis 67
3.2 METHODOLOGY 69
3.2.1 Transdisciplinary Research 69
3.2.1.1 Design Science Research Methodology 72
3.3 RESULTS 75
3.4 DISCUSSION 78
3.5 CONCLUSIONS 80
4 A REGENERATIVE WASTE MANAGEMENT NETWORK FOR THE REGION OF NORTE PIONEIRO, PARANÁ 82
4.1 BACKGROUND 83
4.1.1 Regeneration of Degraded Sites by Waste Disposal 83
4.1.2 Waste Recovery Options 84
4.1.3 Integrated Municipal Solid Waste Management 87
4.2 DESIGNING THE WASTE MANAGEMENT NETWORK 91

4.2.1 SES Description and Purpose Identification 91
4.2.2 Redesign Outputs 93
4.2.3 Network Conceptualisation 96
4.2.3.1 Consumption, Disposal and Collection 99
4.2.3.2 The IMSWM Network 102
4.2.3.3 Regeneration Strategies for Degraded Sites 106
4.2.4 Performance Optimisation 107
4.2.4.1 Mathematical Model 108
4.2.4.2 Computer Model 120
4.3 RESULTS AND DISCUSSION 123
4.4 CONCLUSIONS 135
5 SYNTHESIS 138
5.1 IMPLICATIONS 142
5.2 ORIGINALITY 146
5.3 CONTRIBUTION 147
5.4 LIMITATIONS AND FUTURE RESEARCH 148
REFERÊNCIAS 150
Appendix A – GLOSSARY OF TERMS 178
Appendix B – SUMMARY OF FINDINGS 181
Appendix C – WASTE NETWORK DESIGN PARAMETERS 184
Appendix D – SANKEY DIAGRAM: PROFIT, REGION 6, SCENARIO SR 197
Appendix E – SANKEY DIAGRAM: NET GHG, REGION 6, SCENARIO SR 198

1 INTRODUCTION

There is consensus among many researchers that the effective reversion of environmental degradation requires a radical shift in the way sustainable design have been performed (HOFSTRA; HUISINGH, 2014; LODDER et al., 2014; LOREK; SPANGENBERG, 2014; TURNER, 2014; BORLAND; LINDGREEN, 2013; CUBIÑÀ, 2009; AVLONAS; NASSOS, 2014; REED, 2007; YOUNG; TILLEY, 2006; COOPER, 2005; DYLLICK; HOCKERTS, 2002; MCDONOUGH; BRAUNGART, 2002). In this chapter, the causes of environmental degradation are overviewed, and the current situation of sustainable design and development is presented within the domain of this research: Operations Management - the activity of managing resources to produce and delivery products and services (SLACK et al., 2007, p.4). Latest research advancements on the design of sustainable and resilient supply chains (and networks) are overviewed - some of them featuring this radical shift. The research problem, research questions and objectives are detailed. A novel direction on how to perform the design of supply networks is proposed. The chapter ends with a thesis overview and a list of the publications included in this thesis.

Warnings about the degradation of ecosystems have been systematically given since the middle of the 20th century. In the early 70s, Meadows et al. (1972) predicted an economic collapse at around 2030, causing population levels to abruptly drop to less than one half. This warning was reissued by Turner (2014), after observing that such trend persisted more than thirty years later. Brown (1981) alerted about the intense pressure exerted over ecosystems from the intensive extraction of natural resources: mankind have been operating beyond the “safe operating space” (ROCKSTRÖM et al., 2009), i.e., beyond the capacity of ecosystems to replete resources and absorb the impacts generated by human activities. The most recent warning was given in Allen et al. (2018), the latest report released by the Intergovernmental Panel on Climate Change (IPCC): achieving net zero Greenhouse Gas (GHG) emissions within the next 15 years is crucial to avoid irreversible damages to Earth’s resilience - its ability to cope with disturbances and reorganise without experiencing structural or functional collapses (HOLLING, 1987).

A considerable amount of environmental degradation can be linked with human enterprises, like the production of goods and services primarily focused on economic gains, i.e., business-oriented (DYLLICK; HOCKERTS, 2002; YOUNG; TILLEY, 2006; KLEINDORFER et al., 2005; STEFFEN et al., 2004; MCDONOUGH; BRAUNGART, 2002). Such enterprises led to industrial activities that have been causing the depletion of resources due to intensive raw material extraction, degradation of land from improper waste disposal, and climate change due to GHG emissions. These alterations in the environment mark the *Anthropocene* - the era where changes to the Earth's geology are a consequence of human activity (WATERS et al., 2016). These changes are ultimately the effect of men considering themselves as the most important entities in the universe, where nature exists primarily for their use - or the *Anthropocentrism* (Merriam-Webster.com, 2018; BORLAND; LINDGREEN, 2013).

The Anthropocentric view is so deeply established that even the definition of Sustainability in the Brundtland report is human-centred (HOFSTRA; HUISINGH, 2014; BORLAND; LINDGREEN, 2013): "the development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (BRUNDTLAND et al., 1987). Through Anthropocentrism, the environment cannot be safeguarded, as it causes a short-term thinking that increases the problems in the medium and long terms (LOREK; SPANGENBERG, 2014; BORLAND; LINDGREEN, 2013), and the appearance of rebound effects, where environmental damage is not effectively mitigated, only transferred elsewhere (MURRAY, 2013). A systems-oriented approach is required to revert the damage (YOUNG; TILLEY, 2006; DYLLICK; HOCKERTS, 2002), and, through a transition towards *Ecocentrism* - with nature in a central role, integrated with humans (BARNHILL, 2010) -, societies can remain within the safe operating space delimited by ecosystems (BORLAND; LINDGREEN, 2013; ROCKSTRÖM et al., 2009).

In the field of Operations Management (OM), Sustainable Design has mainly supported the transition from anthropocentrism to ecocentrism through the eco-efficiency and eco-effectiveness approaches. Eco-efficiency (VERFAILLIE; BIDWELL, 2000) means "doing things right" (PORTER et al., 1995) for the environment, aimed at *decreasing environmental impacts*. Through Operations Research techniques, eco-efficiency has been significantly improved. Production systems and subsystems like supply chains have had their environmental impacts decreased through mathematical optimisation, solving problems related with facility location and production planning (BANASIK et al., 2016), routing of perishables (SOYSAL et al., 2014), selection of production processes (JONKMAN et al., 2017), or the distribution of benefits achieved among actors cooperating (STELLINGWERF et al., 2018). Eco-efficiency, however, is considered a business-oriented, anthropocentric approach

(BORLAND; LINDGREEN, 2013), and therefore not capable of reverting the damages caused to the environment.

Eco-effectiveness means “doing the right things" for the environment, aimed at *increasing environmental benefits* - and therefore, ecocentric by nature. Concepts like Positive Externalities (LODDER et al., 2014) were developed, accounting for the benefits that a system cause to the surroundings, like avoiding GHG emissions (LIU et al., 2017). Through Upcycling, new functions are assigned to objects that lost their primary function (MCDONOUGH; BRAUNGART, 2013). Nature have began to inspire man-made design, in the new branch of Biomimetic Design (COHEN; REICH, 2016). New business models were developed, integrating backcasting and eco-design (MENDOZA et al., 2017), and innovative Business Canvas were proposed (UPWARD, 2013). The final phase in the transition from anthropocentrism to ecocentrism is the **Regenerative Design and Development**, characterised by understanding the environment and, supported by stakeholders and the community, resources and ecosystems are regenerated, rather than depleted (MANG; REED, 2012).

The Circular Economy has been advocated as a regenerative economic systems, since it substitutes the concept of end-of-life by restoration, adopts renewable energy, excludes the application of toxic chemicals and aims to eliminate waste (MACARTHUR, 2012). It is based in three main principles (Ellen MacArthur Foundation, 2015): one, to restore and enhance natural capital - linking the Circular Economy with environmental regeneration -, two, optimising resource yields, and three, foster system effectiveness. The two latter are inspired in the eco-effective approach due to the adoption of closed-loops and innovative business models, and in the eco-efficiency approach as it aims to maximise yield with minimal environmental impact. However, if sustainable systems collapse, efforts towards sustainability will not last. To address this problem, researchers have been approaching production systems as Complex-Adaptive Systems.

Systems are *complex* if a dynamic network of interactions can be observed, where the whole is defined by an emerging pattern from these interactions; and *adaptive* if their configuration and behaviour change and self-organise when stimulated by an event (GEELS, 2010; BEHDANI, 2012). Ecosystems became benchmark for the design of production systems, and the concept of Resilience was adapted from ecology to the purposeful design of resilient enterprises and supply chains (FIKSEL, 2006; CHRISTOPHER; PECK, 2004). In this direction, supply networks can be approached as complex systems with multiple levels of analysis (LEVALLE; NOF, 2017; PERERA et al., 2017), leading to a theory on Industrial Supply Networks (ZUO; KAJIKAWA, 2017), and the study of the network topology of eco-industrial parks (LI; XIAO, 2017).

Recently, one major trend in Sustainable Design in Operations Management aims to make production systems more environmentally friendly - or ecocentric - and resilient. Supply Chains (or Networks) that are both sustainable and resilient have been studied in Mari et al. (2014), Fahimnia e Jabbarzadeh (2016), Jabbarzadeh et al. (2017), through methods that optimise the performance of a resilient supply chain. Mota et al. (2018) developed a stochastic model that optimise objectives in the three sustainability dimensions, economic, environmental and profit. Bergendahl et al. (2018) approached supply chain design (SCD) with Transdisciplinary Research (TR), and Gruner e Power (2017) proposed the gradual integration between artificial (supply chains) and natural systems (ecosystems): the “social intergradation". However, the design of production systems, namely supply networks, that are sustainable - merging eco-effectiveness and eco-efficiency, focused on environmental regeneration -, and resilient - adopting resilience principles and quantitative verification - remains an unexplored research opportunity. In the next section, this opportunity will be described, leading to the thesis’ research questions and objectives.

1.1 PROBLEM STATEMENT, RESEARCH PURPOSE AND RESEARCH QUESTIONS

Supply networks have progressed towards ecocentrism by becoming more sustainable and resilient. Still, their contribution to the environment has been mostly limited to the minimisation of environmental impacts, which unleashes rebound effects that can potentially mitigate their contribution. Initiatives focused on environmental benefits and regeneration emerged very recently, after the definition of Circular Economy as a regenerative system. Environmental regeneration has not been adopted as a purpose for supply networks, limiting their contribution in the recovery of degraded ecosystems. This is expressed in the research’s problem statement:

RESEARCH PROBLEM: The design process of supply networks is not focused on the regeneration of degraded ecosystems, therefore not contributing to their recovery in the long term. At best, they cease to damage ecosystems in the medium-term.

There is an urgent need for production systems to *purposefully* engage in the regeneration of ecosystems, reverting environmental damage before the consequences are unbearable. Proposing effective solutions requires merging multiple disciplines in a holistic approach (HADORN et al., 2008): therefore, Sustainable Design (SD) is considered as the broad picture around regenerative design, including multiple approaches towards ecocentric integration. The same consideration is taken with the supply networks, placing them within the domain of Operations Management. The first research question, RQ1, can be posed:

RQ1: *Which disciplines are linked with Sustainable Design research in the field of Operations Management, and how?*

Answering this question leads to a very broad scope of disciplines and subject areas, providing information about the state of the art of SD in OM. Based in this portfolio, the research scope must be narrowed down, so the next research question, RQ2, can be formulated, establishing the object of this research:

RQ2: *What is a regenerative supply network, and how can it regenerate the environment?*

After answering RQ2, a process that supports the design of these regenerative supply networks can be defined, considering disciplines, concepts, and activities in a logical sequence, leading to RQ3:

RQ3: *How can a supply network that regenerates the environment be designed?*

In the next section, the research objectives drawn to answer these questions are described, and the Research Design is presented.

1.2 RESEARCH OBJECTIVES AND DESIGN

This research aims to advance the transition towards the last phase of ecocentrism, regenerative design and development, proposing an artefact: i.e., a structure that, when putted in a specific context, produces a process that leads to an outcome (BOTS; DAALEN, 2012). The “specific context" is the field of Operations Management: this artefact will support the design of supply networks that regenerate ecosystems while fulfilling their function, featuring sustainable performance in the long-term. This aim is represented in the general Research Objective of this thesis:

RESEARCH OBJECTIVE: develop an artefact to support the design of regenerative supply networks.

To develop this artefact, Design Science Research Methodology (DSRM) is used as in (PEFFERS et al., 2007), aimed at providing a scientific ground to the design and development of artefacts from which abstract, scientific knowledge can be extracted (AKEN, 2004). The general objective is cascaded into three specific objectives, each aimed at answering one or more research questions. Research Objective 1 (RO1) is aimed at answering RQ1:

RO1: Identify main authors, most relevant papers, the state of the art of Sustainable Design in the context of Operations Management, and which disciplines are advancing this research stream.

The most relevant articles are defined as those published in high-impact journals, which received a substantial quantity of citations. Most important authors, disciplines, research streams and trends are tracked down to compose a list of the most relevant articles. The RO1 is described in chapter 2, using **ProKnow-C**, a bibliometric review methodology aimed at the formulation of research questions and objectives (ENSSLIN et al., 2013). The next research objective, RO2, is formulated to characterise the artefact being proposed:

RO2: define the Regenerative Supply Network, and propose a procedure for the design process.

The definition of the Regenerative Supply Network is proposed combining multiple disciplines using Transdisciplinary Research. The Regenerative Supply Network (RSND) procedure is developed using DSRM, which prescribes six activities: (i) Identify problem and motivate, (ii) Define objectives for a solution, (iii) Design & Development, (iv) Demonstration, (v) Evaluation and last, (vi) Communication. RO2 is achieved through performing activities (ii) and (iii). Activities (iv) of Demonstration and (v) Evaluation are related with the research objective RO3:

RO3: demonstrate and evaluate the implementation of the Regenerative Supply Networks Design procedure for the design of a waste management network that regenerates ecosystems.

The RSND procedure is demonstrated for the design of a waste management network for the region of Norte Pioneiro, Paraná, and its performance is evaluated on economic, social and environmental dimensions. RO3 aims to complete the answers to the questions RQ2 and RQ3. Last activity, Communication, is performed through conference and journal papers - listed in chapter 5 -, and through this thesis. In the next section, an overview of this thesis is presented.

1.3 THESIS OVERVIEW

Figure 1 is an overview of the thesis, linking DSRM activities with the research questions and objectives. The ellipses representing chapters 1 to 4 are shaped after the extension of the scope of each chapter, as well as the depth of the investigation. In chapter 1 the problem is identified and the motivation to find a solution is detailed.

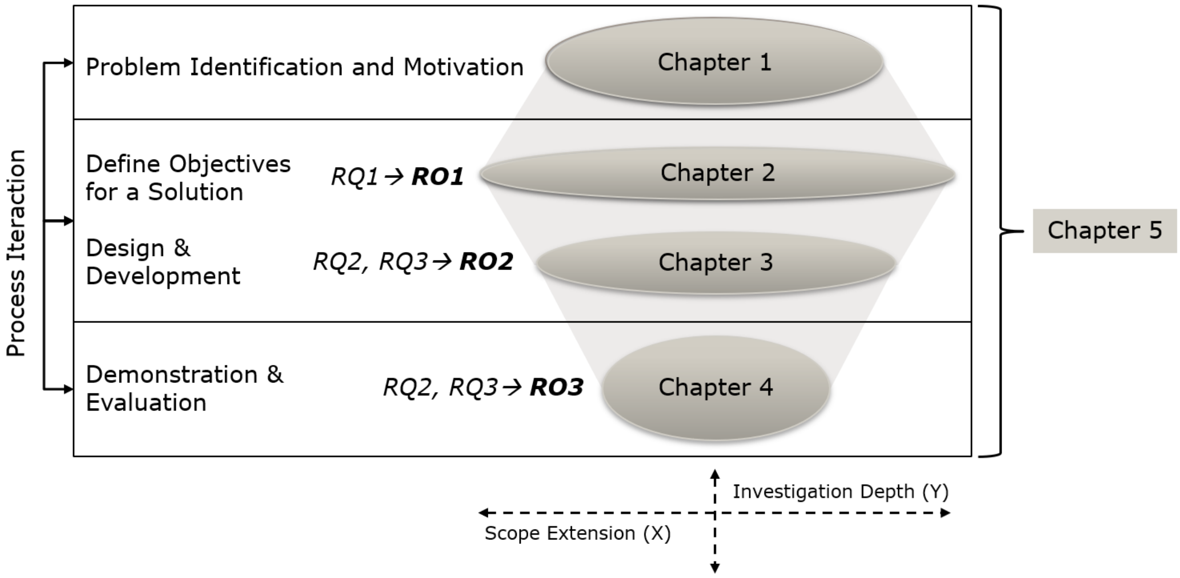

Figure 1: Thesis Overview.

In chapter 2, RO1 is developed to answer RQ1, related with the holistic literature review, wide in scope and shallow in depth, which is represented by the wide, thin ellipse. In chapter 3, objectives for a solution are defined, and the solution, the RSND procedure, is designed and developed, fulfilling RO2 to partially answer RQ2 and RQ3. The focus on Supply Networks implies in a narrower scope than of chapter 2, with an increased depth of investigation. In chapter 4, the artefact is demonstrated and evaluated for the design of a waste management network, fulfilling RO3 and providing elements to complete the answers for RQ2 and RQ3. Therefore, the scope of chapter 4 is narrower, and the depth of the investigation is deepened. In chapter 5, a synthesis of the thesis is provided, with a general discussion, research limitations and future research and contributions.

1.3.1 INCLUDED PUBLICATIONS

This thesis is based on four papers that are either published, in production, under peer review or being prepared. Each chapter is based on specific papers, according to the list below:

In this chapter, a research opportunity is presented: production systems should been

Chapter 2: de Souza, V., & Borsato, M. (2016). Sustainable Design and its interfaces: an overview. *International Journal of Agile Systems Management*, 1(2);

Chapter 3: de Souza, V., Bloemhof-Ruwaard, J. M., & Borsato, M. (2019). Towards Regenerative Supply Networks: a design framework proposal. *Journal of Cleaner Production*, 221, 145–156.;

de Souza, V., Bloemhof-Ruwaard, J. M., & Borsato, M. (in press). Exploring Ecosystem Network Analysis to Balance Resilience and Performance in Sustainable Supply Chain Design. *International Journal of Advanced Operations Management*;

Chapter 4: Souza, V. de, Bloemhof-Ruwaard, J. M., & Borsato, M. (unpublished - to be submitted to the journal *Waste Management*). Designing a regenerative municipal solid waste management network for the region of Norte Pioneiro, Paraná.

designed with a focus on long term environmental regeneration. A solution is proposed for a specific production system, the supply network: a procedure to guide the design of regenerative supply networks, based in eco-effectiveness, eco-efficiency, resilience and transdisciplinarity, developed using DSRM. The research design is presented, and the thesis structure and sequence are overviewed. In the next chapter, the literature review is presented.

2 A HOLISTIC REVIEW OF SUSTAINABLE DESIGN IN OPERATIONS MANAGEMENT

Sustainable Design (SD) can be defined as the interdisciplinary process of creating processes, products and systems using resources and energy without compromising the natural environment, or the ability of future generations to meet their own needs (UNESCO, 2017). As such, performing SD from a holistic approach extends the limits of topics (UNESCO, 2017; HADORN et al., 2008, p.49), providing multiple perspectives, ideas and concepts from different areas and disciplines. Operations Management concerns the production and delivery of goods and services by organisations, involving three main functions: marketing - responsible for communication processes; product/service development - responsible for creating and modifying products and services offered; and operations - responsible for fulfilling the customer requests through production and delivery (SLACK et al., 2007, p. 4).

SD has been applied in a variety of contexts within the field of Operations Management: water supply systems, food production, housing, waste management and sanitation, energy, transportation, industrial processes, conservation of natural resources, cleaning polluted waste sites, restoring natural environments, providing medical care and recommending proper use of technology (HUESEMANN; HUESEMANN, 2011). Improvements and solutions have been developed using Life Cycle Assessment (LCA), Design for the Environment (DfE), Design for Disassembly (DfD), Design for Recycling (DfR), and many others (VALLERO; BRASIER, 2008); advancing SD in OM requires that knowledge is gathered from this multitude of applications.

This review has the objective to understand, from a holistic perspective, how research on Sustainable Design (SD) has progressed in the context of Operations Management (OM), and which directions are being pointed for future research. The methodology is based in the Knowledge Development Process - Constructivism (ProKnow-C), aimed at supporting the definition of research inquiries and objectives. Nine steps are defined, including the creation of a bibliographic portfolio, which is later analysed through bibliometrics and systemic analysis. Bibliometrics reveal the most relevant papers, journals and authors contributing in this context, and subject areas and categories evolving the research stream. A mindmap linking the subject

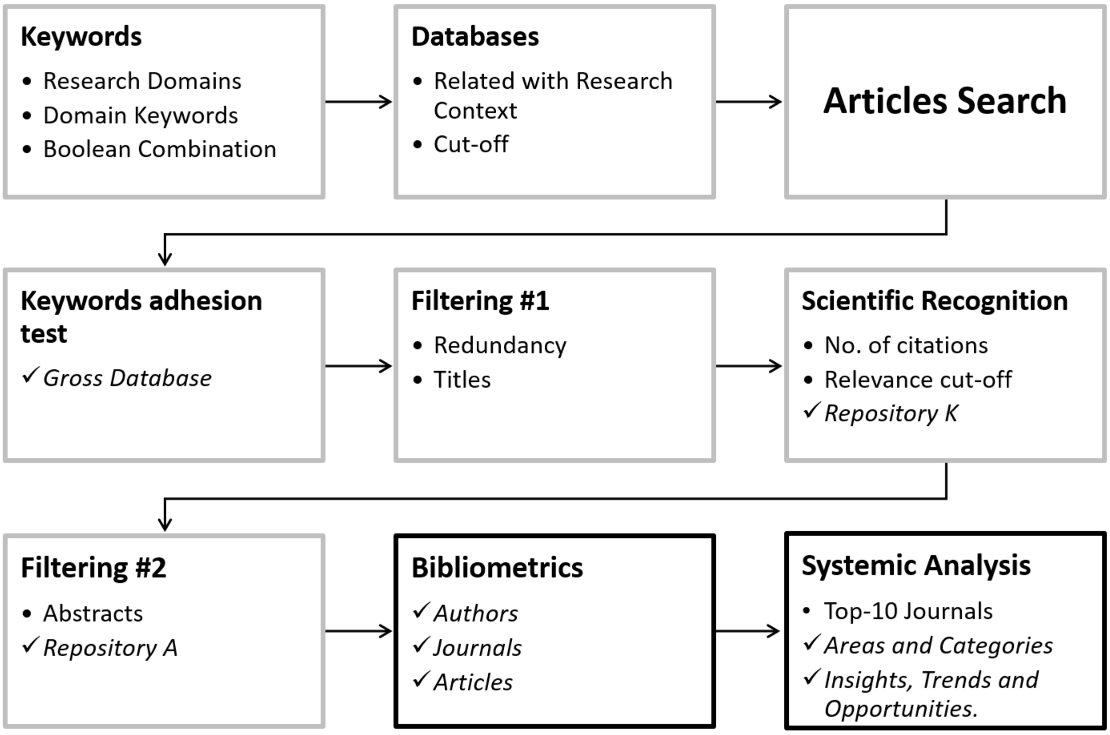

Figure 2: Review Procedure, consisting of three phases: selection of a bibliographic portfolio (first seven grey boxes), bibliometrics and systemic analysis. Based on Ensslin et al. (2013).

areas and research categories is developed and used to categorise the outcomes of the systemic analysis, like research trends and gaps.

This chapter is organised as the following: the review methodology is described in the next section, followed by the bibliometrics and the systemic analysis, organised in subject areas. In the following section, the results of the review are discussed; last, the conclusions and future research are presented.

2.1 REVIEW METHODOLOGY

Knowledge Development Process - Constructivism (ProKnown-C) is a review methodology developed by LabMCDA/UFSC (Multicriteria Decision Support Methodology Lab) of Federal University of Santa Catarina to support the elaboration of research inquiries (ENSSLIN et al., 2013). The ProKnow-C consists of four phases: (i) selection of a bibliographic portfolio, (ii) bibliometrics (iii), systemic analysis and (iv), definition of the research question and objectives. In this review, the three first phases were completed; the fourth phase was not executed since the aim of this review is to provide an overview of SD in OM research stream.

Figure 2 presents the nine steps performed in this review. Each step is represented by one box, containing the activities performed (the dotted items) and outputs - the check-mark

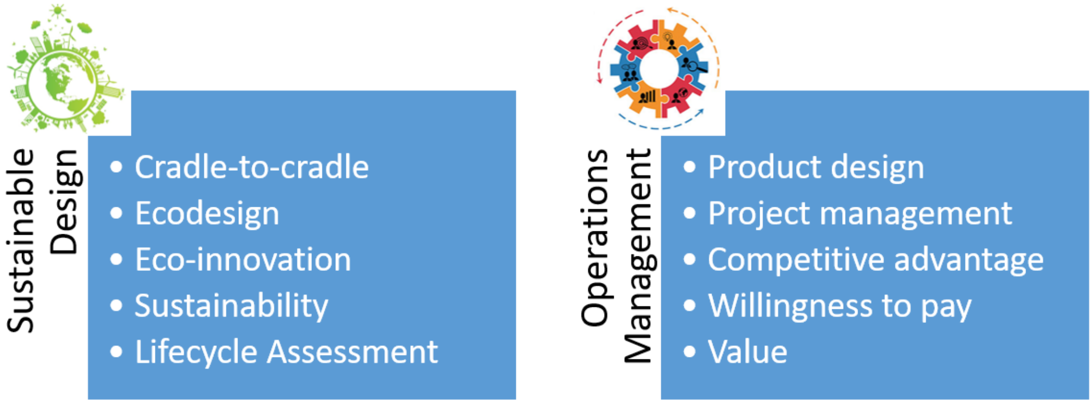

Figure 3: Dimensions and Keywords.

items in italic. The first seven boxes are related with the creation of the bibliographic portfolio related with the research topic; the eighth box, with the bibliometrics, and the last box, with the systemic analysis. The first activity was to define research domains and preliminary keywords: the two research domains are Sustainable Design and Operations Management.

Keywords are defined within each domain, and are listed in Figure 3. In the SD domain, *cradle-to-cradle* is related with the eco-effective approach, defined as “doing the right thing" for the environment (MCDONOUGH; BRAUNGART, 2002). *Eco-innovation* and *ecodesign* (or *eco-design*) are terminologies linked with SD in many researches, while *lifecycle Assessment* is used to measure and quantify environmental impacts, linked with eco-efficiency, or “do things right" for the environment. For the OM domain, keywords defined are linked with the three OM functions of (i) marketing (keywords *willingness to pay* and *value*), (ii) product/service development (keyword *Product design* and operations (iii) (keywords *project management* and *competitive advantage*). The keywords are combined in a Boolean query: (“willingness to pay" OR “value" OR “competitive advantage") AND (“eco-innovation" OR “cradle-to-cradle" OR “ecodesign" OR “Life cycle Assessment") AND (sustainability) AND (“product design" OR “project management").

In the next step, databases are selected according to the search results: if a single result is retrieved, the database is included. The time range selected is from 2004 to 2018. Keywords adhesion task is performed by taking two articles from the list that are strongly related with the topic and comparing its keywords with the ones used primarily. This process was iterative, with four loops to reach the definitive keywords in Figure 3. The list is loaded into Mendeley reference management software. A redundancy check is performed, excluding duplicated articles. Articles go through a first filtering, checking if their titles are aligned with the research topic; those not aligned were excluded. Next, to determine scientific recognition, articles are retrieved in Google Scholar, and their citations registered. A cut-off number of at

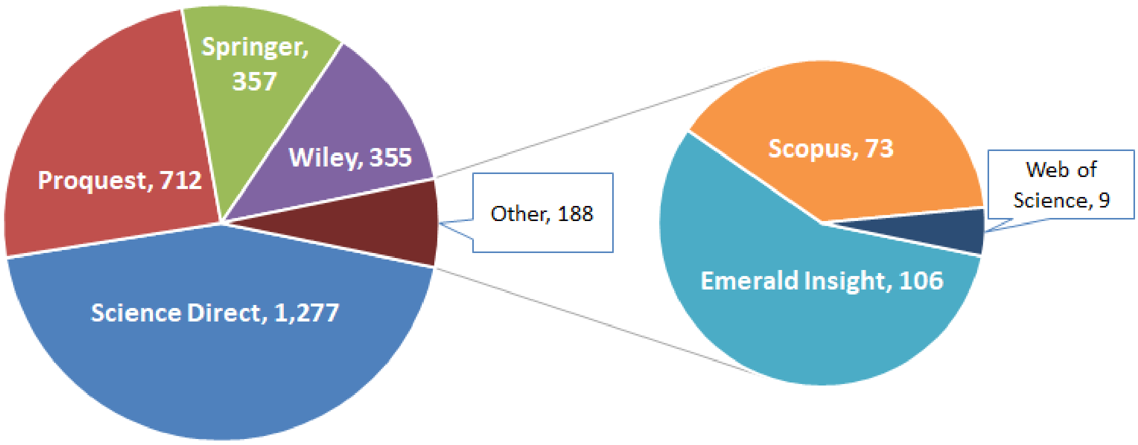

Figure 4: Retrieved articles per database.

least 15 citations is used to define **Repository K**: articles with confirmed scientific recognition. To create **Repository A**, a new filtering is performed with the abstracts: their connectedness with the research topic is analysed. The bibliographic portfolio consists of Repositories A and K.

In the Bibliometrics stage, the portfolio is quantitatively analysed, allowing the identification of main authors, journals and articles published. Microsoft Excel is used to organise the data in tables and graphs. Journals and articles are ranked using impact factor and number of citations. The Systemic Analysis is performed based in the top-10 ten journals with the highest quantity of published articles. For each journal, the areas and categories are retrieved from the Scimago Journal & Country Rank (Scimago, 2018) and a mindmap is created, linking the research topic with its respective areas and categories, for categorisation of trends and opportunities identified.

2.2 BIBLIOMETRICS

Figure 4 shows the databases researched and the number of articles retrieved per database. Science Direct returned the greater amount of results, 1,277, followed by ProQuest (712), Springer (357) and Wiley (355). Other databases searched were Emerald Insight, Scopus and Web of Science, which together sum up to 188 articles retrieved. In total, 2,899 papers were retrieved in the initial search, including duplicates - later excluded. The quantity of articles published from 2004 until 2018 is presented in Figure 5. A polynomial trend line of second order is also added to illustrate the growing trend. One can observe that the quantity of published papers has increased roughly eight times during the last fourteen years, specially from 2009 onwards.

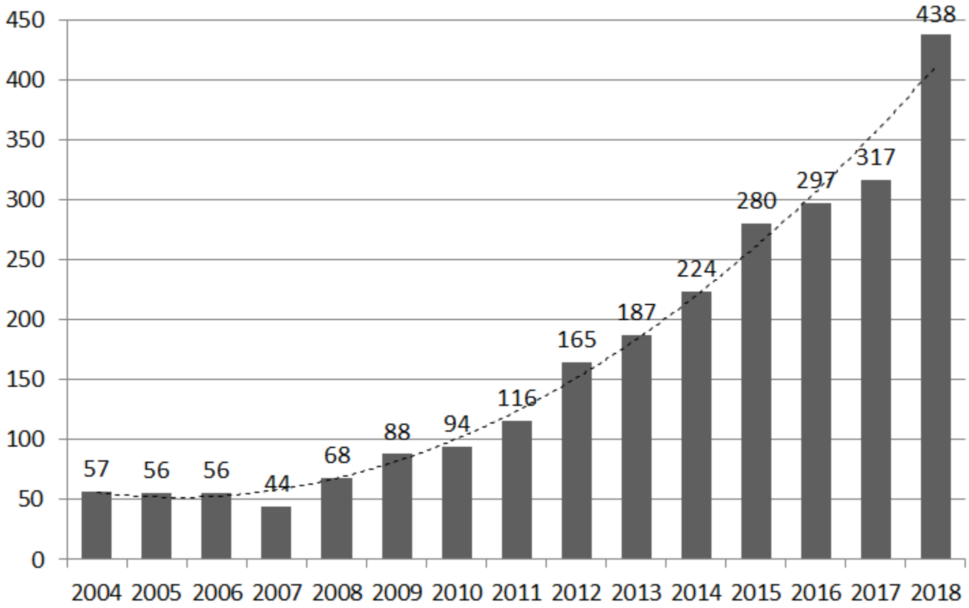

Figure 5: Articles organised by year of publication, per search engine.

Top ten journals with the highest quantity of retrieved articles are ranked in Table 1, with respective Journal Citation Report (JCR) Impact Factor, H-index from Scimago Journal Ranking - both as of 2018 -, and country. Journal of Cleaner Production (JCP), from The Netherlands, is ranked first with 492 articles published and the highest Impact Factor: 5.651. It is also ranked second in H-Index (132), behind the International Journal of Production Economics, also from The Netherlands, which ranks fifth in published articles and Impact Factor. Second journal with most published articles is the Journal of Industrial Ecology, from the United Stated of America, with 127 papers - more than three times less than JCP, ranking sixth in impact factor and seventh in H-Index. Ranked second in Impact Factor is the journal Business Strategy and the Environment, from USA, with 33 published papers, ranked eighth in H-Index - holding the highest discrepancy between Impact Factor and H-Index. The only journal without Impact Factor from the list is the Environmental Quality Management, from USA, ranked last in H-Index. Four journals are based in The Netherlands, three are based in Germany and the last three, in USA.

Table 2 shows the 10-most cited articles as of December 2018; number of citations was acquired from Google Scholar, through software Harzing's Publish or Perish, with respective authors and publication year. The most cited paper is Seuring e Müller (2008) - on sustainable supply chain management -, with roughly the double of citations of the second most-cited, Singh et al. (2009), on sustainability assessment and indicators. In the research stream of green supply chain management and measurement, Hervani et al. (2005) and Zhu et al. (2008) also feature among the most cited. Sharma e Henriques (2005) investigated the stakeholder's

Journal name	Number of papers published	Impact factor[1] (Rank)	H–Index[2] (Rank)	Country[2]
Journal of Cleaner Production	492	5.651 (1)	132 (2)	NED
Journal of Industrial Ecology	127	4.356 (6)	80 (7)	USA
The International Journal of Life Cycle Assessment	102	4.195 (7)	82 (6)	GER
Resources, Conservation and Recycling	47	5.120 (3)	94 (4)	NED
International Journal of Production Economics	47	4.407 (5)	141 (1)	NED
Clean Technologies and Environmental Policy	40	2.343 (9)	37 (9)	GER
International Journal of Advanced Manufacturing Technology	35	2.601(8)	90(5)	GER
Business Strategy and the Environment	33	5.355 (2)	75 (8)	USA
Environmental Quality Management	20	-	22(10)	USA
Materials & Design	20	4.525 (4)	108 (3)	NED

[1] Source: InCites Journal Citation Reports (accessed 12-12-2018);
[2] Source: Scimago Journal & Country Rank (accessed 12-12-2018).

Table 1: Top-10 Journals with Impact Factor.

Article	Title	Number of citations[1]
Seuring e Müller (2008)	From a literature review to a conceptual framework for sustainable supply chain management	3,506
Singh et al. (2009)	An overview of sustainability assessment methodologies	1,875*
Tukker (2004)	Eight types of product–service system: eight ways to sustainability? Experiences from SusProNet	1,612
Hervani et al. (2005)	Performance measurement for green supply chain management	1,279
Sharma e Henriques (2005)	Stakeholder influences on sustainability practices in the Canadian forest products industry	1,056
Reap et al. (2008)	A survey of unresolved problems in life cycle assessment	983
Boons e Lüdeke-Freund (2013)	Business models for sustainable innovation: state-of-the-art and steps towards a research agenda	982
Zhu et al. (2008)	Confirmation of a measurement model for green supply chain management practices implementation	918
Meier et al. (2010)	Industrial Product-Service Systems—IPS2	844
Ilgin e Gupta (2010)	Environmentally conscious manufacturing and product recovery (ECMPRO): A review of the state of the art	843
Kiker et al. (2005)	Application of multicriteria decision analysis in environmental decision making	759

* this paper was re-published in 2012, and its citations are also considered;
[1] as of December, 2018.

Table 2: 10-most cited articles.

influence on sustainable practices, and Boons e Lüdeke-Freund (2013) reviewed business models for sustainable innovation - the latter being the most recent paper on the list. Two papers addressed Product-Service Systems - Tukker (2004) and Meier et al. (2010). Ilgin e Gupta (2010) reviewed environmentally conscious manufacturing and product recovery. Finally, on multicriteria environmental decision-making, the paper of Kiker et al. (2005) is featured in the list. In the next section, the systemic analysis is presented with qualitative evaluation of the bibliographic portfolio.

2.3 SYSTEMIC ANALYSIS

Figure 6 presents the subject areas and categories related with Sustainable Design in Operations Management. Nine subject areas are represented in the grey boxes: Business, Management and Accounting; Economics, Econometrics and Finance; Engineering; Medicine; Environmental Science; Decision Sciences; Energy; Materials Science; and Social Sciences. Categories are child nodes of each area, represented in the white boxes. The systemic analysis was not exhaustive, covering the categories and subject areas linked through solid lines in the figure.

2.3.1 MANAGEMENT, MONITORING, POLICY AND LAW

First, Policy and Law researches are reviewed, followed by management studies and last, monitoring. Lorek e Spangenberg (2014) claimed that even the world most developed countries can be considered, at best, “less unsustainable”. Only through targeted policies people can decrease consumption. It is not expected that enterprises lead initiatives towards sustainable development; the authors claim for government leaderships to do it, with a growing engagement from civil society organisations. Nash (2009) reviewed the European Union Sustainable Development Strategy (EU SDS) for the development of sustainable consumption and production (SCP) and sustainable industrial policy action plan. According to the author, the main factors that influence SCP are the use of resources, product design, available technologies and consumer demands. Three priorities are established: Smarter Consumption - promoting producer and consumer awareness of the effects of their choices, monitoring the effectiveness of regulations on eco-design, energy and eco-labelling. Leaner Production - subject of many regulations, for pollution prevention and control, including small and medium enterprises; and Global Action - investment programmes to foster SCP internationally. The paper also mentions key points to the effectiveness of regulations: stakeholders must act together, consumer knowledge must be increased, and voluntary agreements.

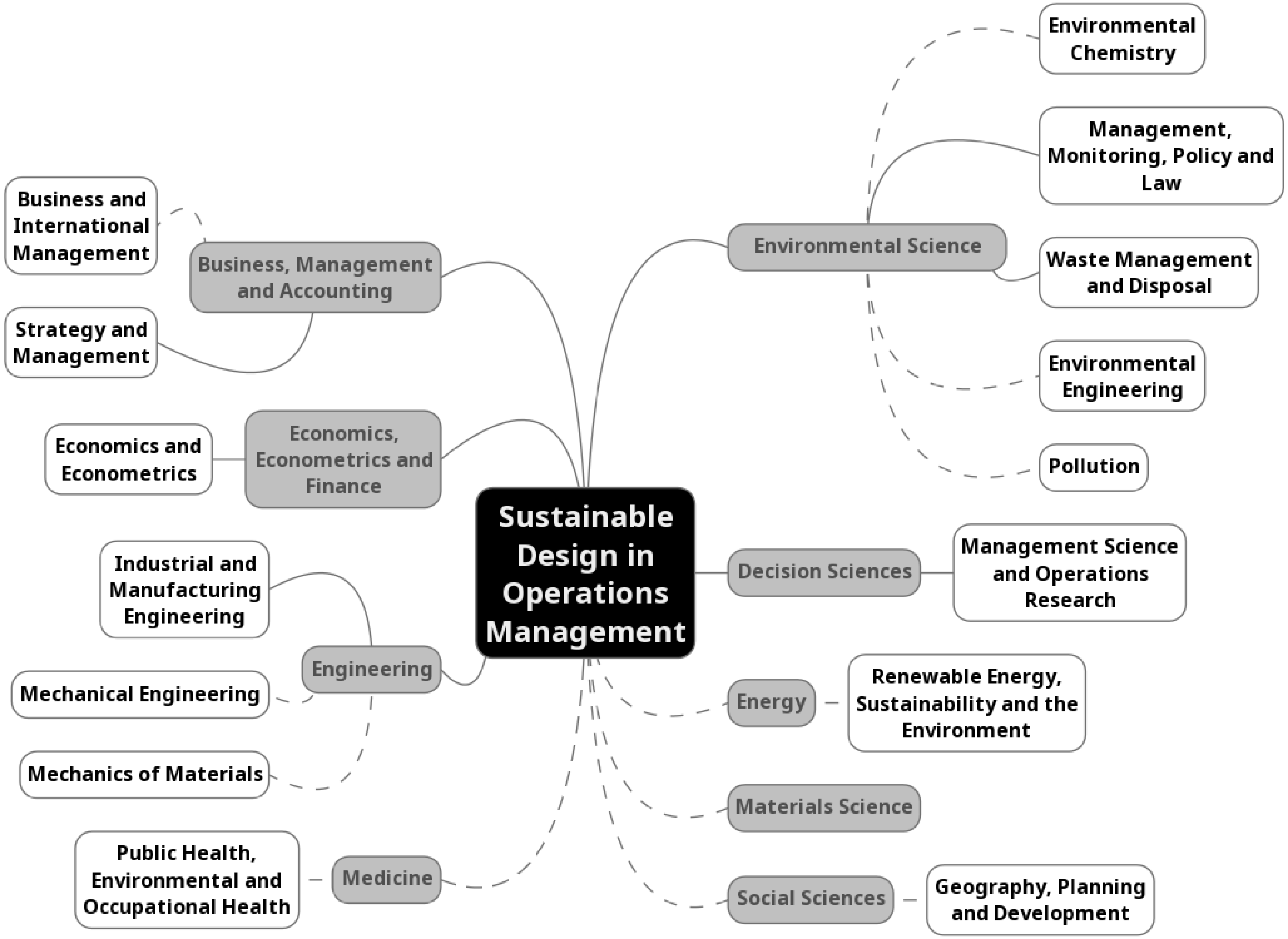

Figure 6: Mindmap of subject areas and categories.

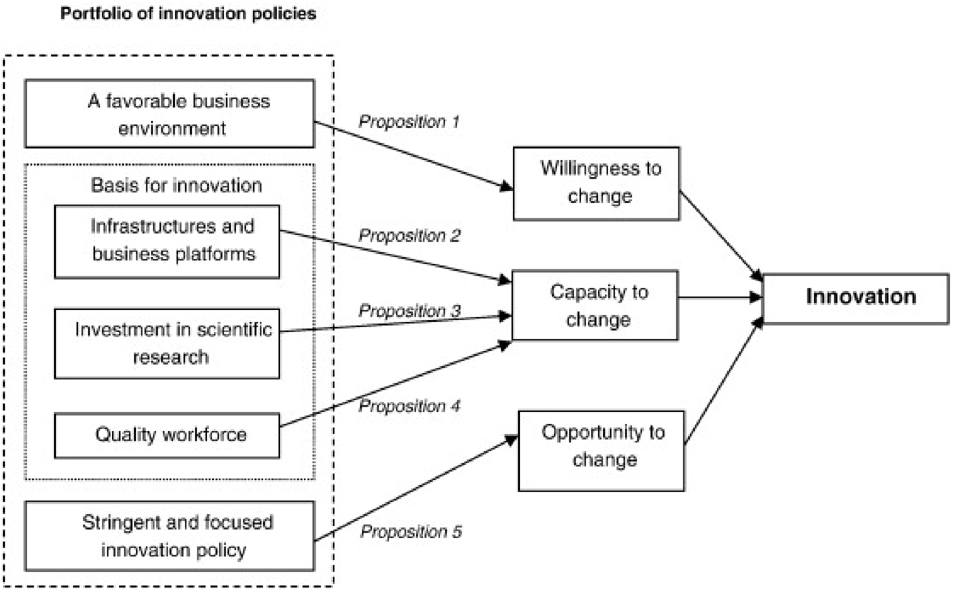

Figure 7: A framework for understanding the roles of government policy and innovation. Source: Patanakul e Pinto (2014).

Malcolm (2011) investigated the Integrated Product Policy (IPP) and the Ecodesign Directive 2009/125/EC, in the context of European Legislation. The author stated that IPP is revolutionary due to its holistic approach, despite using an anthropocentric jargon: “minimising impact with enhanced customer service". The advancement, the author stated, is that the policy now focuses on the product (preventive), not anymore on the processes (vertical approach). The Ecodesign Directive is aimed at improving the environmental performance of products, integrating environmental aspects since the beginning of the product design, until the end of its life cycle. The author also discusses issues like product longevity; desirable in the short term, while extending a product lifespan may delay the adoption of newer products with better environmental performance. The balance between the impact generated by replacing a product and impacts avoided by adopting a new one should be pursued, although difficult to determine.

Patanakul e Pinto (2014) discussed the role of governmental policies on innovation - that can be promoted, but also hindered. They investigated the effectiveness of the implementation of local policies and regulations intended to foster incremental and radical innovation. They propose five propositions, as illustrated in Figure 7, linking the boxes in the far left to the boxes in the middle as potential drivers, which in turn leads to innovation. Proposition 1 is transcribed as an example: “The more the innovation policy creates a favourable business environment, the more it enhances the willingness of firms to change, resulting in higher numbers of innovations."

Two emerging research trends are observed on policy: promoting servicising and the implementation of Circular Economy. Plepys et al. (2015) identified which and how policies could promote servicising, reducing material and energy in market transactions, in different levels, such as continental, national, regional and municipal. In some markets, companies may find themselves trapped in paradigmatic business models, and policies could be developed to give incentives to those who attempt to break traditional patterns, as they claim it is the role of policy makers to identify business models with a high potential of achieving sustainable benefits, proposing policies that unleash their potential. Veen et al. (2017) used an agent-based model to understand the potential of the contribution of servicising to decoupling environmental impacts from economic growth, including factors like willingness to pay. Three case studies are developed, two Business to Costumer (car and bike sharing, domestic water-saving systems) and one Business to Business, on crop protection. They claim that policy packages, rather than isolated policy instruments, tend to be more effective in stimulating servicising.

Hughes (2017) investigated the implementation of the Circular Economy policy package in the European Union, enforcing the use of life cycle assessment and action. They highlighted that the package will also have to tackle changes from Industry 4.0 and the Internet of Things, which have the potential of making many products obsolete. Milios (2018) points out that three areas have been poorly utilised for policy making: (i) reuse, repair and remanufacturing, (ii) green public procurement and innovation procurement and (iii), improving secondary materials markets. He argues that a systemic view is required to handle the complexity during the development of policies, providing a diagram which depicts the European Union policy landscape. Three main challenges are pointed for implementing Circular Economy: first, the increasing global population requires consumption and production policies; second, 100% reciclability is impossible to achieve, therefore the product's lifespan should be expanded; third, current material flows will not meet the demands in the future - this demand should be fulfilled recovering lost resources through e.g. landfill mining. He also stresses the need to develop the social dimension of Circular Economy.

In the context of management, the integration of studies on Industrial Ecology (IE) – when industries closely located exchange material, energy and water flow - with studies on Management and Policy was discussed in Korhonen et al. (2004). They highlighted three main drivers:

1. Inter-organisational management: the theory of stakeholder management can be used to link corporate environmental management theory to IE. The number of stakeholders to be included in an IE context is far greater than what is normally taken into account, increasing risks, but also opportunities, since the firm operates in unfamiliar areas and

cultures, improving its diversification;

2. Development and Management of industrial ecosystems - which should be, by principle, emergent, self-organised industrial networks. The question raised is: what kind of policies or management approaches should be implemented to stimulate such patterns? Cooperation between public (e.g. local authorities) and private actors is mandatory. Successful industrial ecosystems emerge from a company's leadership, rather than driven by a local authority - although their presence as one of the central actors is considered imperative;

3. Industrial Ecology as a vision and a source of inspiration for management strategy - Successful IE initiatives are able to provide goods like clean air and water, and emissions that nature can absorb. Eco-efficiency is not an adequate strategy since it unleashes the rebound effect - unintended consequences that mitigate the environmental gains achieved. Preservation of diversity of local ecosystems should be a focus. The ecosystem metaphor is important to the transformation process of worldviews and visions towards a more sustainable community.

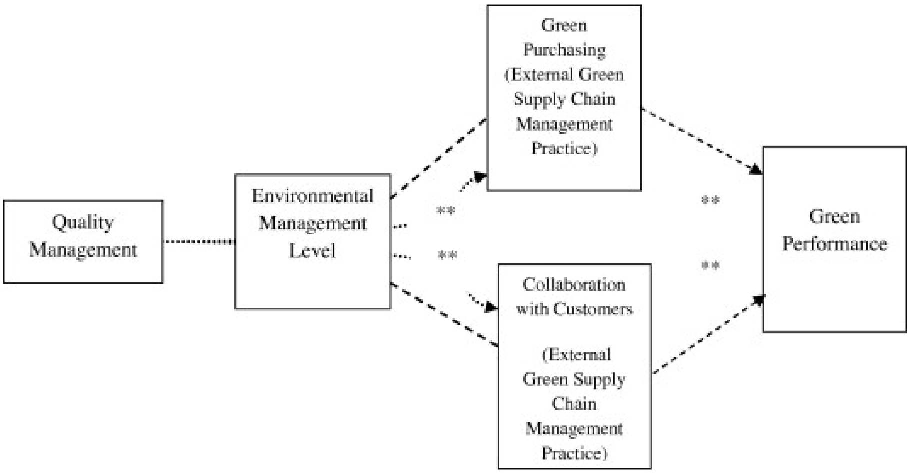

Figure 8: Structural model – indirect/mediating effects.
Note: for $p \leq 0.01$. Source: Jabbour et al. (2014)**

Ormazabal e Sarriegi (2014) defined and validated maturity stages of the evolution of environmental management. Companies start adopting environmental practices from legislation obligations; only later they identify economic benefits from environmental improvement, implementing eco-innovation and becoming driving forces for other companies. Jabbour et al. (2014) proposed a conceptual model linking quality management (QM), environmental management maturity (EMM), green supply chain management (GSCM) and green performance (GP), as illustrated in Figure 8. Data was gathered from 95 ISO-certificated,

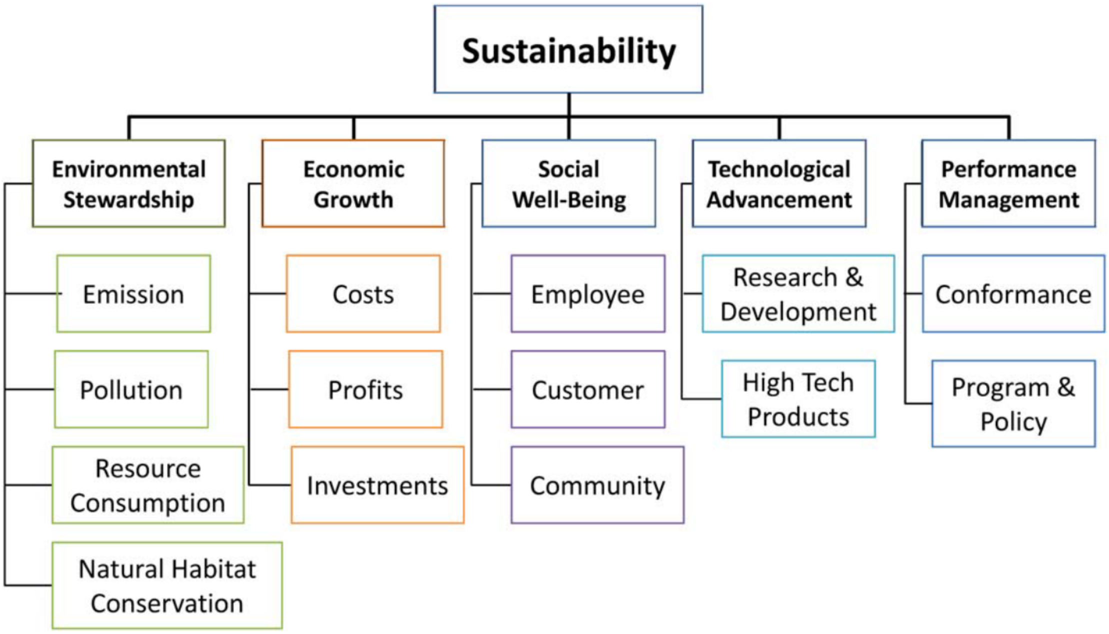

Figure 9: NIST Indicator Categorisation Structure.Source: Joung et al. (2012).

Brazilian firms, and 9 hypothesis where tested. Through EMM, QM influences GSCM practices that ultimately impact Green Performance. Their model can be used by practitioners as guidance to improve green performance.

Management also implies monitoring sustainable performance through environmental impact indicators. Joung et al. (2012) defined the features an indicator must have, e.g., name and unit of measure. Their review follows a categorisation standard from the National Institute of Standards and Technology (NIST) composed of five sustainability dimensions: (i) environmental stewardship, (ii) economic growth, (iii) social well-being, (iv) technological advancement and (v) performance management. Each category is presented with its first-level subcategories in Figure 9. Each subcategory may be unfolded, to the level of the indicators. This article's contributed with a repository of more than 200 indicators, and with a process to select indicators process composed of eight steps.

Singh et al. (2009) performed a review of indicators with a wide scope: starting from different frameworks that define sustainability indicators, the authors reviewed multiple ways to approach sustainability assessment. They brought an overview of 41 indicators, e.g., Summary Innovation Index (SII), Human Development Index (HDI), Sustainability Performance Index (SPI), Ecological Footprint (EF), Dow Jones Sustainability Group Indices (DJSGI), Life Cycle Index (LInX), Eco-Indicator 99. They also described a methodology to formulate indexes, aggregation strategies and guidelines to combine two or more indicators, addressing problems like uncertainty, data inaccuracy and proper weighting. Rodrigues et al. (2017) provided a repository of 141 management performance indicators to measure the implementation of ecodesign practices during the product design process.

Life Cycle Assessment (LCA) is the most used and accepted methodology to perform sustainability assessment (NESS et al., 2007; FINKBEINER et al., 2014). It has been used in a wide range of applications, from biotic-resource depletion caused by fishing (LANGLOIS et al., 2014), decision-making for ship retrofitting (BLANCO-DAVIS; ZHOU, 2014), vehicle development (ARENA et al., 2013) and food systems (ARZOUMANIDIS et al., 2013). Finkbeiner et al. (2014) points challenges and opportunities for research in LCA, like accounting for the effects of nanomaterials in human health, microbiological pollution, and noise. They highlight that careful should be taken not to over-interpret LCA results. LCA studies also have shortcomings: they can be time and efforts consuming, due to its range of possibilities (MAYYAS et al., 2012; VINODH; RATHOD, 2010). Premises defined may distort results achieved (SEOW; RAHIMIFARD, 2011). There is also a heavy dependence on data availability: as an example, Labuschagne e Brent (2006) faced difficulties to complete a proper evaluation due to data unavailability.

Accounting for social sustainability can be seen as a major trend of SD in OM. Tang e Zhou (2012) observed that the OR/MS (operations research/management science) community has just started defining and measuring social sustainability - the “people” dimension in the triple bottom line. The UNDSD (United Nations Division for Sustainable Development) defined six themes for social sustainability: Equity, Health, Education, Housing, Security and Population. Each theme can be measured with at least one indicator (HUTCHINS; SUTHERLAND, 2008). Corporate Social Responsibility (CSR) is pointed as one of the concepts that help decision makers enrolling in social sustainability. Other social indicators can be found in Labuschagne e Brent (2006). To measure the sustainability of industrial processes, three indicators can be highlighted: Greenhouse gases (GHG), exergy and emergy. Carbon Dioxide Equivalent (CO_{2eq}) is the unit of measure for GHG emissions, because CO_2 is involved in the majority of global warming process, taking longer to leave the atmosphere: about 20 per cent will still be around 800 years after it was emitted (Ucsusa-1, 2015).

CO_{2eq} was used in Norgate e Haque (2010) to evaluate the impact of mining and mineral processing operations. They discovered that efforts to mitigate GHG emissions should focus on loading and hauling (for iron ore and bauxite) and grinding processes (for copper ore). Kim et al. (2006) investigated the optimal replacement policy for refrigerators, minimising CO_{2eq}, energy and cost objectives for a time horizon between 1985 until 2020, recommending why and when one should replace his/her refrigerator. Bocken et al. (2011) developed an ideation tool to design products that reduces significantly GHG emissions, while Barandica et al. (2013) evaluated road construction projects. This wide range of applications demonstrates the versatility of CO_{2eq} as a measurement for environmental sustainability.

The concept of Exergy appeared for the first time in Rant (1956), but it was initially discarded as scientists believed it overlapped with Gibbs' free energy (SCIUBBA; ULGIATI, 2005). Exergy is defined as a representation of "the maximum work that we can extract from a system by means of ideally reversible transformations that bring it to a state of complete (statistical) equilibrium with its reference state" (SCIUBBA; ULGIATI, 2005). Differently from energy, exergy is not conserved through systems, but consumed in real processes while entropy is produced, complying with the second law of thermodynamics (SZARGUT, 2005). As a thermodynamic indicator, exergy is normally measured in MegaJoules - MJ.

Emergy is defined as the solar energy needed to obtain a product, or used in a process, whether direct or indirectly (SCIUBBA; ULGIATI, 2005). It is also not conserved, such as exergy. It is based in the concept of Transformity, which is the amount of input emergy dissipated per unit output exergy (SCIUBBA; ULGIATI, 2005). Odum (1973) defined a set of symbols, the *Emergese*, to describe the emergy flows, which can be used to describe multiple flow types like mass, energy and currency, including dissipating flows. An example of this diagram describing exergetic flows using emergese is illustrated in Figure 10.

Emergy is regarded with scepticism by exergists, as can be observed in Sciubba (2001, 2011). In Sciubba (2001), both measures are discussed on their advantages and limitations. Transformities are difficult to calculate, and infringe the second law of thermodynamics (SCIUBBA, 2010). Exergy, in the other hand, fails on properly account for flows like information and culture, considered as natural driving forces. Both approaches have progressed on accounting for externalities: exergy through Extended Exergy Accounting (EEA). Finally, the authors agree that EEA is appropriate for process representation, while Emergy analysis is suitable to investigate the interconnections between a process with environmental dynamics. Examples of recent exergetic analysis can be found in Almeida et al. (2017b), Lu et al. (2017), and emergy in Almeida et al. (2017a), Corcelli et al. (2017).

2.3.2 STRATEGY AND MANAGEMENT

Marchi et al. (2013) investigated the outcomes of the adoption of green strategies by four Italian companies, driven by customer strategies or entrepreneurship. Value chain approach was used in strategic management analysis: the relationship with the customer was deepened in three companies. Schoenherr (2012) investigated the influence of sustainable business

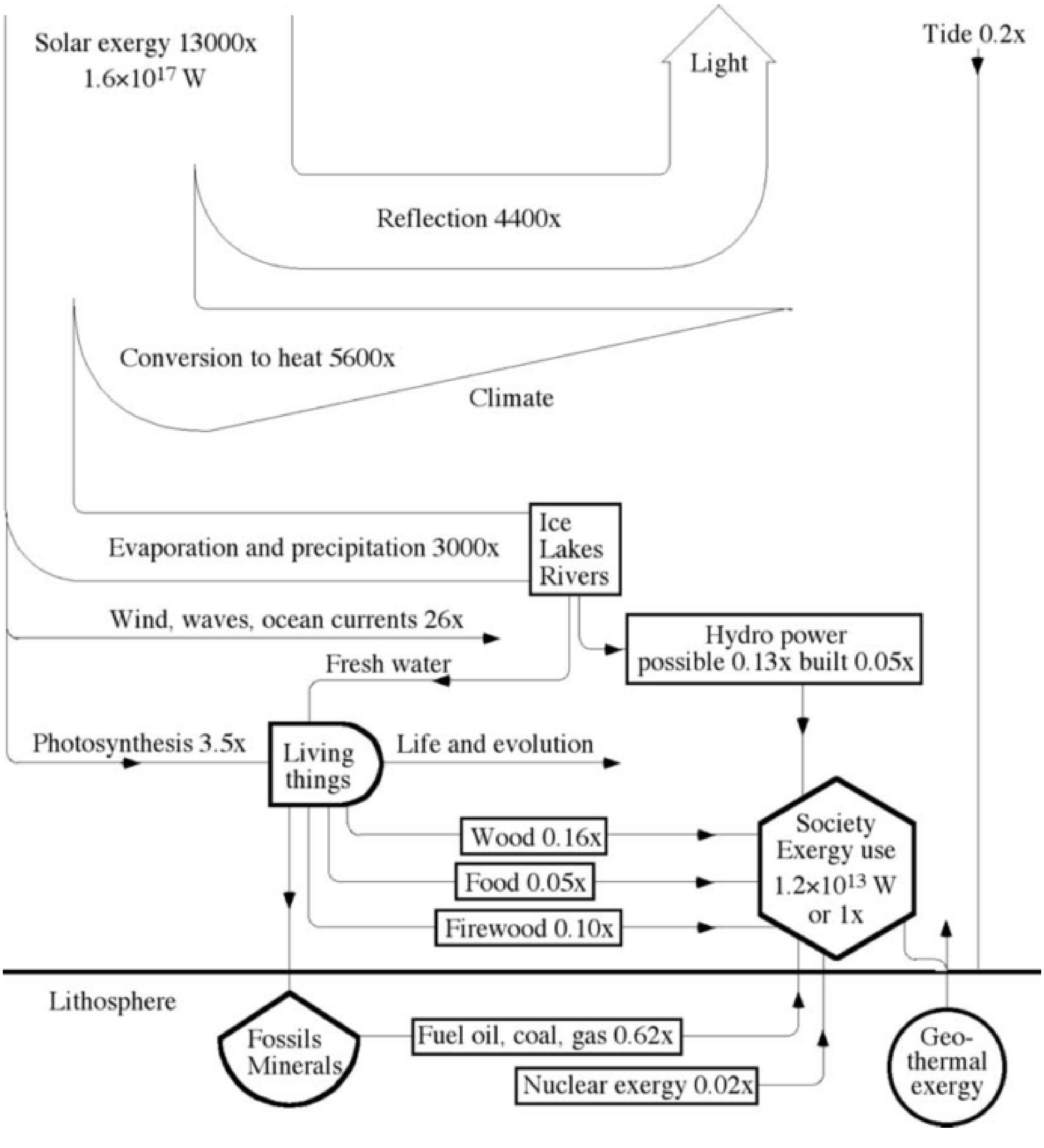

Figure 10: Exergy flows on earth represented with emergese.Source: Wall e Gong (2001).

development over operations in manufacturing plants. A survey with 1,211 manufacturing plants spread over 21 industrialised, emerging and developing countries was performed, based in four main initiatives: ISO 14000 certification, pollution prevention, recycling of materials and waste reduction. Four competitive capabilities were assessed: quality, delivery, flexibility and cost. Statistical tests confirmed positive effects over performance for three out of four initiatives: only recycling showed non-significant results. They concluded that the type of environmental strategy adopted was influenced by the degree of the country economic development. They pointed as a future research differentiating direct and indirect effects on plant performance, quantifying their relative contribution.

In the field of waste recovery strategy choice, Lieder et al. (2017) attempted to answer an intriguing question: which strategy is the most sustainable, considering the business model and supply chain under study? They developed a simulation model and quantified the environmental impacts and costs of multiple design options for a washing machine, generated under different business models (buy-back, leasing and pay-per-use) in a search for a sustainable, cost-effective solution. The simulation model is multi-method, combining an agent-based model to simulate the decisions during the design of the product's components, and a discrete event model to simulate a circular supply chain, using a 15-years scenario to optimise the option developed under the pay-per-use business model.

Zhang e Wang (2014) used regression models to investigate the effects of inter-firm collaboration to reduce GHG emissions in the firms' performance. A survey was conducted with Chinese energy-intensive industries to understand cooperation mechanisms, drivers and effects on performance. Industrial symbiosis (IS) is often used as a cooperation mechanism, while the main driver to engage in GHG emissions reduction is stakeholders demand, weather it comes from suppliers or customers. Financial pressure is a positive driver for cooperation among competitors. Regulation was found not to have any effect. Collaboration through IS improves a firms' environmental performance, which in turn improves their economic performance.

Longoni et al. (2014) studied the improvements achieved with the implementation of New Forms of Work Organisation (NFWO) in social sustainability. Teamwork, training and employee involvement were among the strategies assessed, and they confirmed positive effects of Training - considered of having a fundamental role - on environmental and social sustainability, and positive interaction with social programs. Involvement and incentives have positive effects on social sustainability, and teamwork has positive interaction effect with management programs of complex environmental problems. They stressed the importance of using strategic orientation rather than top-down approaches, and suggested using qualitative approaches to investigate the effectiveness of holistic human resources measures on sustainable performance. They also suggested the elaboration of a single sustainability construct that takes into account performance in the three pillars, since a strong correlation between environmental and social dimensions was found.

Borland e Lindgreen (2013) explored ecological sustainability and ecocentrism to reconceptualise strategic marketing. They pointed that integrating the duality of human and nature's needs remains a big challenge on building an ecocentric strategic theory. They classified eco-efficiency as a transitional strategy, while eco-effectiveness, cradle-to-cradle and loop-closing, as transformational strategies. They proposed a definition for the ecocentric transformational marketing strategy: "companies that satisfy the needs of industrial and consumer markets remaining within biophysical constraints, only exploiting resources at a rate at which they can be sustainably maintained, recovered or replenished in cradle-to-cradle, closed-loop ecological systems." They suggested that many future contributions can be given in this direction.

Hofstra e Huisingh (2014) questioned the definition of sustainability in the Brundtland report, for being anthropocentric-oriented: to guarantee **human's** needs. They highlight four perspectives for human-nature relationship: contradiction, separation, connection/connectivity, and union. They also discussed the paradigm shift, putting nature in a central role. Eco-innovations are classified in four types: exploitative - focused only on meeting regulations; restorative - that doesn't challenge current business models, maximising eco-efficiency; cyclical - based on connectivity between humans and nature; and regenerative - where the ecosystem is understood and value is added to both human and nature. A taxonomic classification for eco-innovations is proposed, comparing the anthropocentric and ecocentric views.

The Circular Economy has been boasted as an alternative to the linear economy, decreasing dependency on non-renewable and virgin materials (BERMEJO, 2014), as well as Product-Service Systems (PSS), a mix of tangible products and intangible services designed to jointly fill one consumer needs (TUKKER, 2015). PSS has faced implementation problems, due to the resistance to cultural change shown by customers, when they sense that ownership or freedom was lost. The authors point that result-oriented services have the maximum potential to achieve environmental benefits, while product-oriented PSS does not deliver major contributions to a Circular Economy. Efforts should be spent to promote PSS designs that enhance the customer's experience. Lindahl et al. (2014) generalised such initiatives around the concept of Integrated Product Service Offering (IPSO), using LCA and Life Cycle Costing to quantify the environmental benefits of three case studies. Environmental and economic performance were improved in all cases, in different levels. Common enablers for the implementation of IPSO were flexible contracts, and close contact between suppliers and customers.

2.3.3 MANAGEMENT SCIENCE AND OPERATIONS RESEARCH

The application of decision-making methods have added a very important contribution to Operations Management. Theodosiou et al. (2015) integrated environmental principles during the design and planning of energy systems, using LCA and Multi-Criteria Analysis. They developed a multi-objective optimisation model to minimise environmental impact and financial cost. The solution was a balanced mix between non-renewable and renewable energy sources. As future research, they suggested using exergy as an optimisation parameter, and sensitivity tests to support the definition of legislation and policies. Wheeler et al. (2018) combined multi-objective optimisation with multi-attribute decision making (MADM), generating a Pareto frontier through weighting factors for the design of a biomass supply chain. They used four well-established MADM techniques: SWING, SMART, AHP and TRADE OFF, and the resulting supply chain topology varied according to the different weights provided by each method. The paper contributes on handling conflicting objectives from multiple stakeholders and still reaching optimal design solutions.

Xu et al. (2015) studied the impact of introducing a carbon-tax system during the product design process, and the resulting chain reaction. An algorithm was developed to decompose the problem, resulting on a “triple-win fulfilment" of customer, enterprise and government requirements, solved with multi-objective optimisation. They suggested tax rates that could fill both the government and enterprise’s requirements. García-Diéguez et al. (2015) developed an integrated Ecodesign performance index, based in Fuzzy Programming. They demonstrated the tool with a children footwear case study, ranking the shoes designs by their performance.

Nouira et al. (2014) developed optimisation models to support the selection of manufacturing processes and inputs (components) considering environmental impacts, studying the correlation between environmental performance, demand and price. Demand changes according to the product “greenness". Jayal et al. (2010) underpin that a holistic approach is needed to achieve a global, optimised sustainable performance, including manufacturing systems and processes. They also stress the importance of the life cycle approach to understand the extension of the environmental impacts. Ondemir e Gupta (2014) explored optimisation techniques to the groundbreaking technology of Internet of Things (IoT), applying

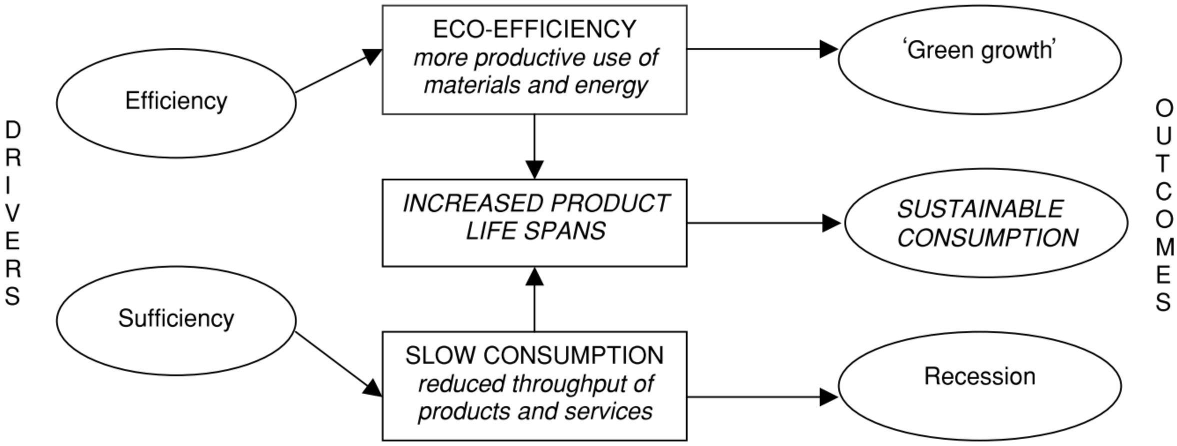

Figure 11: Product life spans and sustainable consumption.Source: Cooper (2005).

a mixed integer goal programming modelling in the proposition of remanufacturing-to-order and disassembly-to-order systems, focused on product's end-of-life.

Decision-making methods were overviewed in Khalili e Duecker (2013), and a framework was proposed for the design of sustainable environmental management systems (SEMS) that incorporates multi-criteria decision making (MCDM). They observed that one major challenge faced by companies is to effectively perform benchmarking. Stoycheva et al. (2018) used MCDM and transdisciplinarity to understand the tradeoffs between the economic, environmental and social dimensions, combining managerial decisions with material criteria and performance. Four weight distributions were used: balanced - even distribution between the three dimensions -, automotive industry (OEM) - privileging the economic dimension -, green company - focused on environmental performance -, and NGO, focused on the social dimension. In the weighting distribution of the OEM, ferrous metals were the most preferred material; in the other three weighting distributions, organic composites showed better performance.

2.3.4 ECONOMICS AND ECONOMETRICS

In this section, economic aspects of consumption and market agents are overviewed. Cooper (2005) stated that a decrease in the consumption patterns incurs on changing from a linear to a circular economy. He proposes slowing down the consumption rhythm, using as examples the Slow Food and Slow Cities movements. He proposes a conceptual model, represented in Figure 11, where sustainable development is driven by efficiency and sufficiency. Eco-efficiency is widely accepted by industries, leading to “green growth" as the throughput of products and services is reduced. On the other hand, slowing down consumption may lead to unemployment and recession, which also harms sustainability. He argues that increasing product lifespan can lead to sustainable consumption: a cultural change would be required, since part of the population is not willing to possess products in the long-term.

What would be the side effects if people became “green”? Murray (2013) argued that it is better to reduce consumption of a less sustainable product than keeping the same consumption levels with a more sustainable product. As an example, when a customer changes a combustion car for an electric one, he is tempted to use the car more frequently, ultimately spending the savings on more consumption. To understand environmental benefits and impacts, The author classified attitudes as efficiency choices (changing technology) and conservation choices (decrease usage), modelling the rebound effects for each choice. The greater the cost savings with environmental solutions, the greater is the rebound effect, mitigating a solution’s effectiveness. Buhl et al. (2017) explored how a Living Labs environment could be used to effectively monitor and mitigate rebound effects in the early stages of product and service design.

With this growing concern on sustainability issues, Leonidou et al. (2013) studied the role of green marketing programs in firm’s performance. Companies are unlikely to abandon their current market positions to target environmentally conscious customers. They grouped green marketing programs in four clusters:

1. Green product programs, related with decisions on product conceptualisation;
2. Green pricing programs, giving financial benefits to incentive greener consumption, or penalties from the consumption of unsustainable products;
3. Green distribution programs, targeted at improving environmental performance of the firm’s demand chain and;
4. Green promotion programs, aimed at communicating stakeholders about the company’s efforts and achievements on sustainability.

Seven hypothesis correlating these programs with external drivers and outputs such as product-market performance were tested, as structured in the conceptual model in Figure 12. Their findings show that green product and distribution programs are more effective on propagating the companies’ green efforts than green pricing and promotion programs. Risk aversion and slack resources are drivers of green marketing programs. They pointed future research opportunities on examining the effects of these programs on customers, and studying their reactions to different program components. Choi et al. (2018) examined how market competition influences the adoption of Green Supply Chain Management (GSCM) practices,

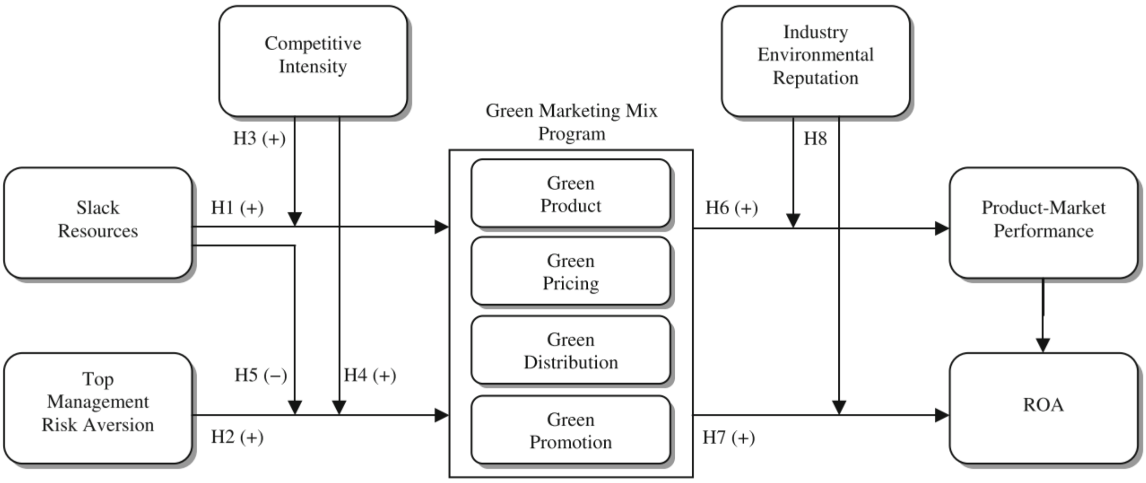

Figure 12: Hypothesis testing for green marketing. Source: Leonidou et al. (2013).

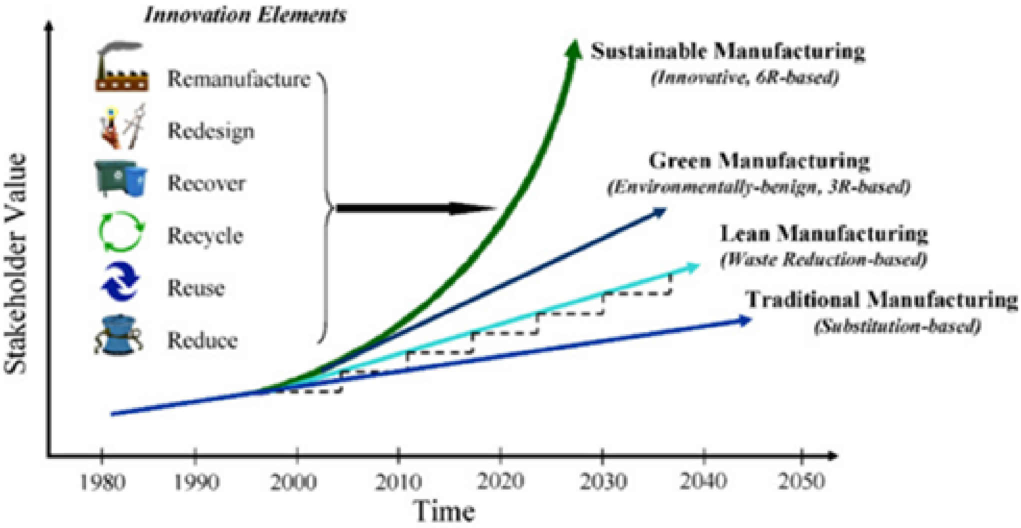

Figure 13: Evolution of sustainable manufacturing. Source: Jayal et al. (2010).

using data from 322 Korean firms. They found that Green Purchasing has the highest impact on marketing and manufacturing performance. They also pointed the most effective practices for those companies that remain sceptical to adopt GSCM practices.

To engender sustainable consumption patterns in the future, major changes in product design and industrial principles are required (SPANGENBERG et al., 2010). These changes are highlighted in the following subsection.

2.3.5 INDUSTRIAL AND MANUFACTURING ENGINEERING

Jayal et al. (2010) reviewed modelling and optimisation challenges at product, process and system levels, or supply chains. They pointed that Sustainable Manufacturing (SM) adds more value to stakeholders than green, lean and traditional manufacturing, as it is based in

6R: reduce, reuse, recover, redesign, remanufacture and recycle. Through SM, stakeholder value can be exponentially increased in time, as depicted in Figure 13. In the product level, divergences in LCA weighting from the perspective of the manufacturer and the consumer, and techniques to deploy and evaluate sustainable principles are highlighted. In the process level, they evaluated machining technologies on six elements: environmental friendliness, personnel's health, operational safety, waste management, power consumption, and machining cost. In the system level, they claimed that closing loops are heavily dependant on product design; therefore, product and supply chain design should be linked.

Aguado et al. (2013) proposed a model to implement efficiency and sustainability improvements in a lean production system. Claiming their model is highly generalizable, they explained the business transformation with a case study. They stated that the adoption of environmental innovation improves competitive advantage. Smith e Ball (2012) uses a Material, Energy and Waste (MEW) flows method to reach a similar conclusion: environmental and financial benefits can be achieved decreasing inputs and reducing waste outputs. They successfully applied the methodology in an industry. Despeisse et al. (2012) used MEW to link operations, facilities and buildings within their proposition, modelling the factory environment as an ecosystem, from the premise that the surrounding infrastructure should be added to the scope of a manufacturing system.

Another trend widely explored is energy consumption management. Seow e Rahimifard (2011) presented a framework for the 'lean energy', advising a mature use of the available energy by choosing the most efficient processes. They modelled the embodied energy of a product to understand which manufacturing process demanded more energy. Duflou et al. (2012) reviewed efforts in the efficient and effective use of resources with a multi-level approach, focused on energy efficiency. Actions were categorised using levels of scale: unit process (machine redesign, allocation and optimisation), multi-machines system (exergy cascading, optimisation), factory (simulation, factory layout, production planning), multi-facility (Industrial Symbiosis) and supply-chain levels (location, regional energy generation).

Materials selection is another task with major influence over product sustainability, according to the nature and life cycle duration of the product studied. Allione et al. (2012) proposed the MATto, a material library containing samples for new materials based on its most relevant environmental features. The database allows the designers to choose suitable materials according to product definition, scope and function: for products with a short life, it is better to use materials that are easier to recycle. Mayyas et al. (2012) reached the same conclusion after a LCA study of an automobile body-in-white: material choice should be performed depending on the product longevity.

Still in the context of automotive industry, Ribeiro et al. (2008) developed a material selection methodology based in Life cycle Engineering (LCE) using Life cycle Costing. Applying weights to life cycle stages, they compared six different materials used in the manufacturing of a vehicle front fender balancing technical, environmental and economical performance. Focusing on the end-of-life phase, Schaik e Reuter (2007) linked vehicles recycling rates with design. They used fuzzy models as an interface between CAD and recycling models, predicting the recycling rate of the vehicle in the design stage, as a basis for Design for Recycling. This work can be used as a reference to properly calculate the recycling rates of new vehicles.

Another major trend identified concerns the environmental performance of additive manufacturing (AM). Ford e Despeisse (2016) evaluated the impacts of additive manufacturing on sustainability, finding benefits in the life cycle of products and materials. Challenges in the development of this technology, and implications on business models and value chains configuration are discussed. Kellens et al. (2017) Examined the sustainability impacts of AM in terms of energy consumption, claiming that it consumes considerably more specific energy than conventional processes. The lack of data on the life cycle impact of AM prevented a more thorough evaluation, also revealing a research opportunity to perform life cycle assessment of AM from other perspectives than energy consumption.

AM features considerable environmental gains when dealing with small batches and when a part redesigned through AM offers substantial advantages to its functionality. Tang et al. (2016) investigated the design of an engine bracket comparing the traditional CNC with the AM technology of binder-jetting. They developed a framework to account for the design freedom inherent of AM, capable of unleashing major environmental benefits. The part achieved a better functional performance with less energy consumed and GHG emitted. Other studies also approached AM from a supply chain perspective (THOMAS, 2016) and studying social impacts (MATOS; JACINTO, 2019).

2.3.6 WASTE MANAGEMENT AND DISPOSAL

Morrissey e Browne (2004) categorised and analysed three types of waste management models, according to their purpose: cost-benefit, life cycle or multicriteria analysis. Municipal Solid Waste Management has been approached holistically since the 1980s; disposal behaviour was already a research topic from the early 90s. Lately, policy has pushed towards the inclusion of multiple waste recovery options in waste management models, towards an Integrated

Solid Waste Management (ISWM). A comprehensive list of MCDA and LCA software tools was presented. Current models balance the compromise between economic and sustainable performance. The authors claimed that no model considered all three sustainability dimensions, economic, social and environmental. Future research points towards the development of systemic models which consider a broader number of stakeholders.

Major progresses in Solid Waste Management (SWM) still have to be accomplished in developing countries. Marshall e Farahbakhsh (2013) points the main drivers: public health, modernisation of SWM, resource scarcity and waste value, climate change, and public concern and awareness. Barriers pointed are: urbanisation, inequality, and economic growth; cultural and socio-economic aspects; policy, governance, and institutional issues; and international influences. They stress the need for applying post-normal scientific methods and complex, adaptive systems thinking. Blomsma (2018) reviewed and discussed ten waste and resource management frameworks to foster constructive engagement: Product Life-cycle System, Performance Economy, Material Efficiency, The Blue Economy, Cradle-to-cradle, Sustainable Materials Economy, Waste Hierarchy, Industrial Symbiosis, The Natural Step, and Regenerative Design. These frameworks are denominated collective action frames - CAFs, defining a language and a conceptual toolbox to properly apply and manage these frameworks.

Figure 14 illustrates the ISWM paradigm, centred on the balance of three dimensions: environmental effectiveness, social acceptability, and economic affordability (MARSHALL; FARAHBAKHSH, 2013). The diagram suggests that the entire context should be considered to understand what kind of waste is generated, prior to defining what types of prevention, reduction, recovery and disposal methods should be adopted in the ISWM system. Smith et al. (2015) investigated four distinct technologies to recover value from organic waste: incineration with energy recovery, gasification, anaerobic digestion and fermentation, considering electricity and ethanol as the outputs. The technology with the best environmental performance was anaerobic digestion, featuring also economic benefits, together with gasification and fermentation. They stress the need to perform local, contextualised assessments when selecting waste recovery processes.

Still in the context of developing countries, Wang et al. (2012) studied dismantling and handling of heavy and precious metals of electronics industry - the e-Waste. They proposed the “Best-of-two-Worlds" philosophy, integrating technical processing and logistics in multiple stages to configure a complete recycling chain. The authors bring insights over geographic distribution of activities, using as an example the dismantling of a desktop computer, with sensitivity analysis for variations of labour cost, resources market prices and data availability.

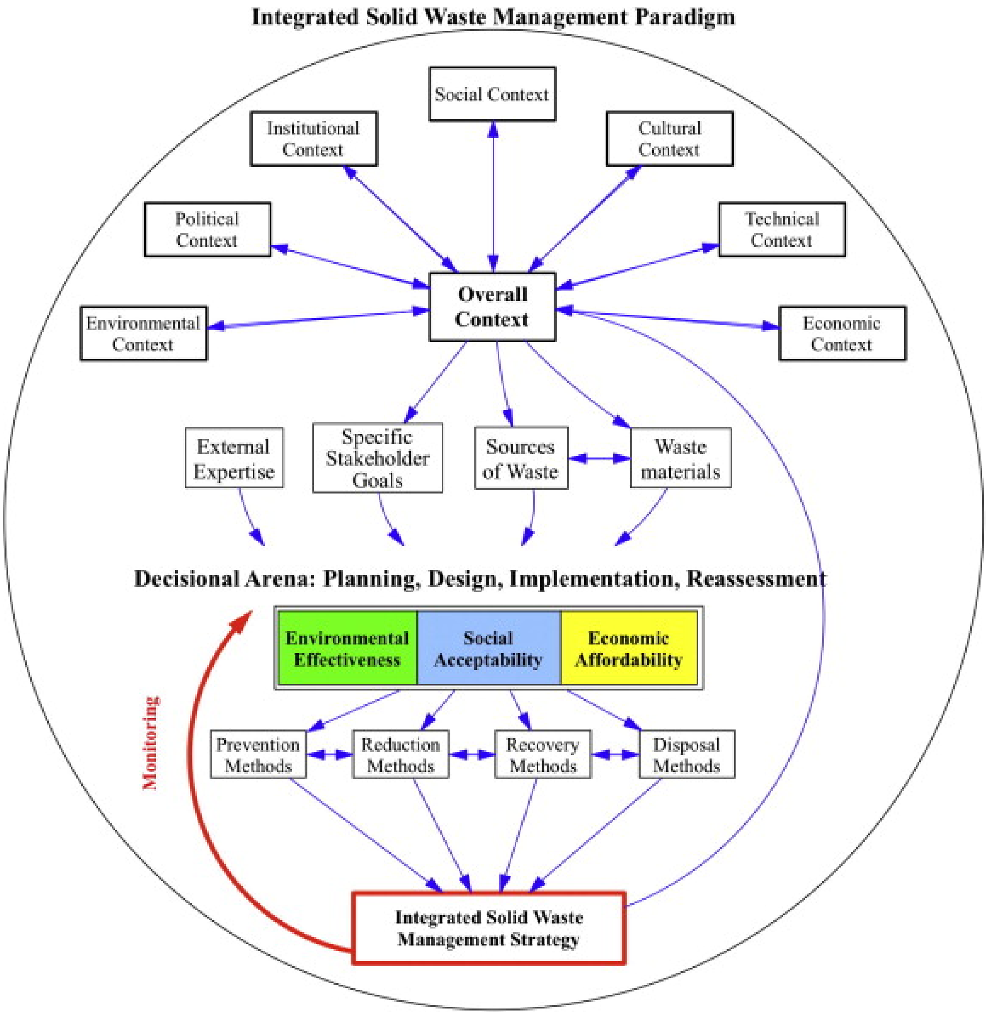

Figure 14: Integrated solid waste management. Source: Marshall e Farahbakhsh (2013).

They concluded that the most sustainable solution for developing countries is to locally pre-process e-waste by manual dismantling, delivering critical fractions of material to high-tech, globally distributed processing facilities. This philosophy has a high impact on social sustainability, considering that manual dismantling is mostly performed by low-income labour.

Another trend in waste management is the Enhanced Landfill Mining (ELFM), aimed at reintroducing landfill waste in a productive chain - enhanced stands for more environmental-friendly valorisation processes. Passel et al. (2013) defined a 5-step procedure to estimate a total number of potential sites to perform ELFM, based in the trade-off between private costs and environmental benefits, measured with net GHG emissions - avoided minus emitted GHG. From the societal perspective, large areas could be restored and used for housing, recreation and natural reserves. For the region of Flanders, Belgium, ELFM projects have had positive outcomes in the three dimensions.

Polymers are considered among the most difficult materials to handle in the end-of-life. Al-Salem et al. (2010) reviewed their processing, studying Plastic Solid Waste (PSW) recovery flows. The paper thoroughly describes the recovering processes of re-extrusion - primary recycling, very efficient to process onsite scrap -, mechanical recovery - for mixed plastics, or plastics discarded after a certain number of cycles -, chemical recovery - for the conversion of plastics into monomers or petrochemicals, for fuel production -, and energy recovery - mostly through incineration within the municipal solid waste management, reducing dependency on fossil fuels. They defended that chemical and energy recovery represent sustainable solutions to the PSW cycle, as both routes already reached a mature development level.

2.4 DISCUSSION

In this section, this review is compared with other reviews, and holistic approaches are also discussed. In a similar review, but with a narrower scope, Hare e Mcaloone (2014) investigated the relation of eco-innovation with the dimensions of strategy and management, and environmental science, approaching both relations as interfaces in a top-down approach. They also stressed the importance of a systemic approach, using LCA to measure performance, and collaborative research, involving multiple domains. This chapter approached the review from a bottom-up approach, starting from a broader perspective, to identify in which categories relevant research was being performed.

Despite holistic approaches look quite similar, they can differ considerably in organisation and structure when their purposes is compared. Ziout et al. (2014) used a holistic approach to guide decision-making for EoL product recovery, merging four views: engineering - i.e., process and product technical factors -, environmental - resources conservation and pollution prevention factors -, societal - targeted segment and overall factors - and business - market, supply and demand, political and legal factors. They claimed that their method includes all stakeholders in the process, which is one of the main research trends identified in this review. They used the four views to define weighting criteria for a particular case study in an automotive industry: the Engineering view receiving the highest weight, followed by business, environmental, and societal. This outcome reveals the business-oriented approach of the automotive industry; in other case studies, this weight distribution could show a different order, depending on the business type.

Blizzard e Klotz (2012) also reviewed sustainable design from a holistic perspective, proposing a framework with twenty elements from sustainable development, systems thinking, engineering, architecture, urban design, planning, and sustainable management. The framework is organised in three overarching categories: design process - outlining essential elements, e.g., practice mutual learning; design principles - the fundamental laws from which methods are derived, e.g., learn from nature; and design methods - procedures for executing a task, e.g., rethink waste. With a very broad focus, their method can be considered a useful foundation for the development of holistic frameworks, specifically for sustainable design in the context of OM.

Fet et al. (2013) proposed a holistic approach focused on life cycle design for the maritime industry, introducing sustainability principles in a Systems Engineering (SE) framework. They defined four main life cycle phases: construction, operation, maintenance and scrapping. The concept of SE is defined within a classic framework, limiting the holistic approach to the scope of life cycle analysis, where the whole life cycle is considered for decision-making in design processes. Other issues like stakeholders or interacting systems impacted by design decisions were not investigated.

2.5 CONCLUSIONS AND FUTURE RESEARCH

This chapter reviewed Sustainable Design in the context of Operations Management, with the objectives of mapping the evolution of SD research related with OM, which are the most important authors, journals and research performed; identifying which disciplines, subject areas and categories were involved in relevant research; and insights, trends, state-of-the-art and opportunities for future research. The review methodology consisted of nine steps based in the ProKnow-C methodology. Dimensions and keywords were defined, databases researched, bibliometrics and systemic analysis were performed. Relevant papers and journals were identified, and the 10-most relevant journals were used to identify the disciplines, represented by subject areas and categories related with SD research in OM. For six categories, insights, trends and opportunities were described. Three principles were stressed in many papers as linked with successful implementation of Sustainability Design in Operations Management:

- **Involving a larger number of stakeholders:** the more stakeholders are included in the initiative, the higher are the chances for success. Apart from the usual stakeholders considered, the holistic approach reveals non-traditional stakeholders that add other perspectives, ultimately improving the quality of a proposed solution. The trade-off is an increased complexity, harder to manage. Ultimately, the extra effort pays off, leading to positive outcomes;
- **Using LCA to assess sustainable performance:** the approach is consolidated in the research community for communicating sustainability performance, due to the variety and extension of scope it has been explored to quantify sustainability through multiple research communities. It has become a common language among researchers, despite of criticism on the reliability of its results, that should neither be used to bias decision-makers nor be taken as indisputable evidence;
- **Integration** of sustainability principles into classic research instances like decision-making, management, strategy, product design. The improvement of the quality of solutions proposed for sustainability problems can be associated with the increasing integration of disciplines. Such a strong theoretical assumption cannot be ignored by researchers seeking progress in Sustainable Design for Operations Management.

The definition of subject areas and categories using the Scimago classification is a limitation of this review; other approaches could be used, changing the categorisation of the systemic analysis. The author understands that this is a minor shortcoming, since the multidisciplinary aspect would inevitably emerge. Other keywords could also be chosen, leading to a different article portfolio, which also could reveal other authors and research perspectives. Findings showed a very broad pattern, since broad dimensions were defined, namely Sustainable Design and Operations Management; therefore, no subject could be explored in depth. It can be argued that every holistic initiative is at risk of loosing sight of the main objective, when seeking to capture multiple aspects, levels and dimensions. However, it allowed the construction of a rich portfolio of articles, widening the perception around of the multiple perspectives of SD applications, which could not be achieved through a narrower perspective.

Many authors found that economical performance of an organisation is positively influenced by the implementation of sustainability principles (ZHANG; WANG, 2014; MARCHI et al., 2013; SCHOENHERR, 2012; SMITH; BALL, 2012; AGUADO et al., 2013; LEONIDOU et al., 2013). These papers contribute to the theory on SD, sending an important message to entrepreneurs: engaging in sustainable strategies is not a burden, but a profitable opportunity to explore new markets on the pursuit of a more sustainable society.

3 A PROCEDURE TO DESIGN REGENERATIVE SUPPLY NETWORKS

Industrial activity have provided humanity with wealth levels like never seen before in history (Ellen MacArthur Foundation, 2015; Richard Kersley; STIERLI, 2015), but not without severe consequences to the environment and society: together, industrial processes and fossil fuel account for 65% of the Global Greenhouse Gas Emissions (IPCC, 2014). Downey e Willigen (2005) stated that the mental health of neighbours surrounding industries was negatively impacted, while Turner (2014) reinforced the predictions of a societal collapse warned in Meadows et al. (1972). All these problems can be regarded as an effect of Anthropocentrism - a view where the human being is at the centre of the universe, and nature exists to serve to his purposes (BORLAND; LINDGREEN, 2013; Merriam-Webster.com, 2018).

In the field of Sustainable Supply Chain Design (SSCD), the fight against environmental degradation began through eco-efficiency*,[1] (VERFAILLIE; BIDWELL, 2000), aimed at keep the economic performance levels of a company and reducing environmental impacts. However, as a business-oriented approach (DYLLICK; HOCKERTS, 2002; YOUNG; TILLEY, 2006), even with companies adopting such strategy, environmental problems continued to worsen (HAUSCHILD, 2015; TURNER, 2014). The eco-efficient approach is disciplinary, and generates unintended, negative side effects, while sustainability represents a complex challenge that can hardly be tackled by a single discipline (MAUSER et al., 2013; SAHAMIE et al., 2013). Inter- and multi-disciplinary systemic approaches were proposed, trying to avoid two problems observed in traditional, reductionist research (ACKOFF, 1999):

- Taking separate parts and improving them separately will not result in the improvement of the whole;
- Problems are not disciplinary in nature: “effective research is transdisciplinary”.

Transdisciplinary Research (TR) is a way forward to address the problem of

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[1] Concepts with an asterisk are further described in the glossary of terms in Appendix A.

sustainability, reaching “the common good” (BERGENDAHL et al., 2018; BRANDT et al., 2013; SAHAMIE et al., 2013), which can be interpreted in different ways (HADORN et al., 2008). TR should be applied when (i) there is not enough reliable knowledge about the problem, (ii) there is dispute over which practices must be transformed and (iii) solutions proposed shall have a profound impact in the whole society (HADORN et al., 2006). In line with the premises of TR, the eco-effective* approach Braungart et al. (2007), Carrillo-Hermosilla et al. (2010) aims to propose effective solutions to sustainability problems, as it is focused on generating environmental benefits. Concepts like biomimetics*, upcycle* (MCDONOUGH; BRAUNGART, 2013), Industrial Symbiosis* (CHERTOW, 2000; LOMBARDI; LAYBOURN, 2012), Circular Economy (Ellen MacArthur Foundation, 2015) and Biobased Economy* (LOPES, 2015) are based in this approach, and seek to achieve ecocentric systems, with nature as a central element, integrated with men (BARNHILL, 2010).

Initiatives combining eco-effectiveness and eco-efficiency can be found in Niero et al. (2017), which proposed a framework based in both approaches to design a closed-loop packaging system. (BANASIK et al., 2016) optimised the performance of a mushroom closed-loop supply chain* that reintroduces waste as raw material. Still, in order to deliver environmental benefits in the long-term, supply chains (or networks) must be able to deal with external disturbances without losing their function - an ability called resilience. Research on SSCD has advanced in this direction: Fahimnia e Jabbarzadeh (2016) used mathematical modelling to optimise sustainable performance and resilience during SC design, investigating dynamic trade-offs. Based in Ecocentrism, Gruner e Power (2017) proposed the “social intergradation" - a gradual, mutually beneficial integration between the social and ecological dimensions of sustainability, enhancing also resilience of operations and of ecosystems. Advancing SSCD towards TR, Bergendahl et al. (2018) used the transdisciplinary approach in a food-water-energy nexus* project, performing multi-level analysis to understand interrelationships.

However, a supply chain design framework focused on environmental regeneration, advancing the transition from anthropocentrism towards ecocentrism supported by both eco-effectiveness and eco-efficiency, based in Transdisciplinary Research and addressing the ability of Resilience could not be found in the literature. In this chapter, this gap is filled by proposing a definition and a procedure for the Regenerative Supply Networks Design (RSND) process - taking the broader perspective of *network*, rather than *chain*. The RSND procedure is approached as an artefact* and developed using the Design Science Research Methodology. Through the RSND procedure, a supply network can be designed focusing on environmental regeneration, while its sustainable performance is assured through optimisation techniques.

The design procedure consists of four steps, where (i) the network surroundings are depicted as a Socio-Ecological System, and a regenerative purpose is defined. With an eco-effective approach, based in Circular Economy, (ii) network inputs and outputs are redesigned. (iii) The supply network is conceptualised as a Socio-Technical System: its interactions with the surroundings are mapped and resilience is addressed. In step (iv), the performance of the supply network is optimised, generating multiple network configurations according to the strategy adopted, and its resilience is quantified using the Ecosystem Network Analysis (ENA) model (ULANOWICZ, 2000). The remainder of this chapter is organised as follows: Section 3.2 presents the background; in Section 3.3, methodological procedures are described. Section 3.4 includes the RSND definition and the framework. In Sections 3.5 and 3.6, discussions and conclusions are provided.

3.1 BACKGROUND

The main concepts related to the RSND development process are organised in the process diagram in Figure 15, in terms of how each concept supports the development process. The outputs of the process are (i) a definition for the regenerative supply network, (ii) a definition for the design process, and (iii) a design procedure. The inputs used are twofold: advancing in the path towards ecocentrism through the design of sustainable supply chains. The elements used in the process are in the box *With What*. The concept of chains is expanded into networks; both the SES and the STS views are used to depict systems and interactions; the circular economy model is used as a benchmark, and resilience principles are adopted. Metrics used to assess the the process are in the *Metrics* box, and they measure the performance of the output - the Regenerative Supply Network -, in terms of its Sustainable Performance and Resilience - the latter quantified through the Ecosystem Network Analysis. *Who* conducts the process, is the author, using Transdisciplinary Research and Design Science Research Methodology - box *How* -, both described in the Methodology Section. Each element is reviewed in the subsection number indicated in the Figure.

3.1.1 PATH TO ECOCENTRISM

The path towards environmental regeneration is defined by the transition from anthropocentrism – which is degenerating the environment -, to ecocentrism, as represented in Figure 16 (MANG; REED, 2012). As human consciousness gradually integrates with nature, it evolves from using resources indiscriminately to an efficient use, then towards resource conservation. Anthropocentric efforts to reduce degeneration like eco-efficiency* - “doing

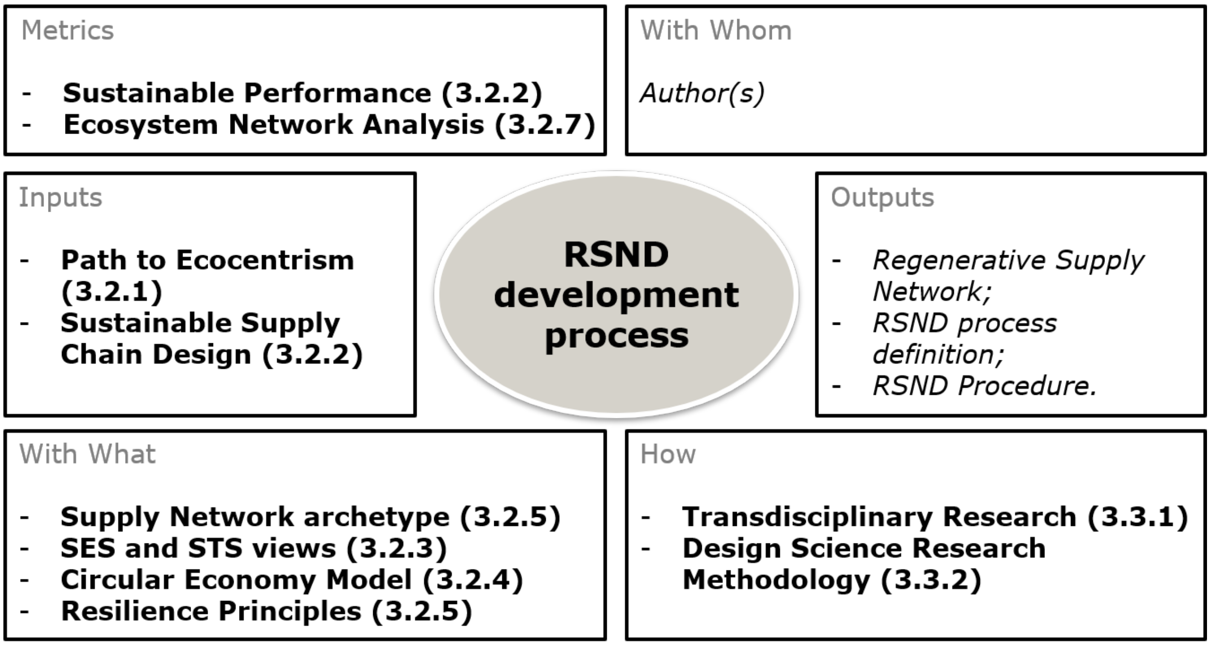


Figure 15: Process Diagram of the RSND development process, categorising the concepts used in the procedure.

things right" for the environment (DRUCKER, 1995, p.33) are business-oriented (YOUNG; TILLEY, 2006). As such, they generate rebound-effects, where gains are likely to be lost by increased consumption – e.g., using more frequently an electrical car because it is electric (BJØRN; HAUSCHILD, 2013). With a shift to ecocentrism, nature affiliation ("biophilia") begins, then evolves to mimic nature (biomimetic), restore nature, tend nature and finally, be nature – achieved through regenerative design and development, respectively (MANG; REED, 2012).

$$eco - effectiveness = \frac{Achieved}{Desired} \ [degree\,of\,regeneration] \qquad (1)$$

Restorative design returns damaged sites to "a state of acceptable health through human intervention" (MANG; REED, 2012). Regeneration is achieved when "the ecosystem is understood and value is added to both human and nature." (HOFSTRA; HUISINGH, 2014). The regenerating stage is marked by nature-oriented approaches like eco-effectiveness, i.e., to "do the right thing" for the environment, which can be defined by the ratio between the degree of regeneration achieved and the degree desired. This relation is represented in Equation 1, based on Enright (2012).

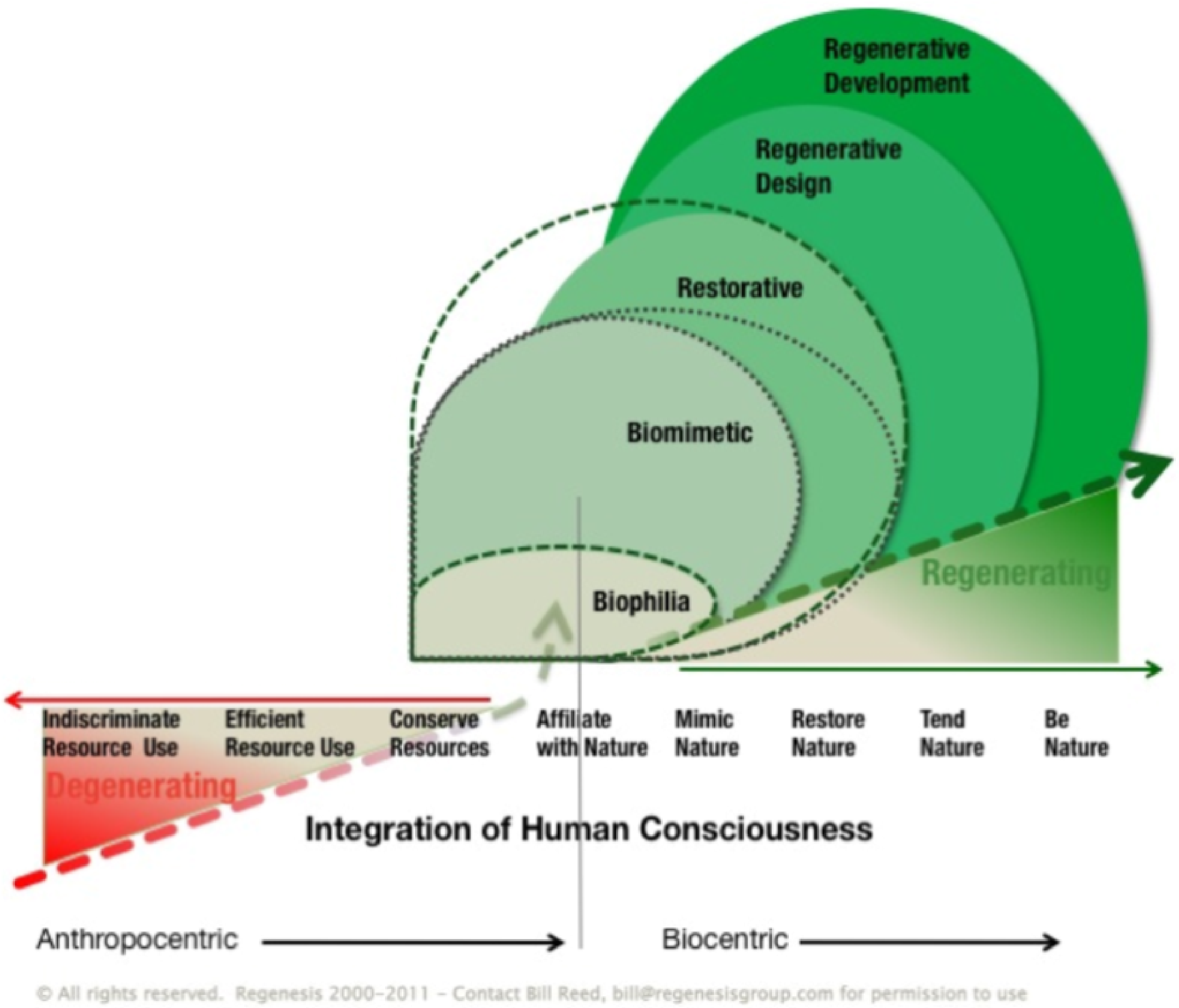


Figure 16: The path towards Regenerative Development. Source: Mang e Reed (2012).

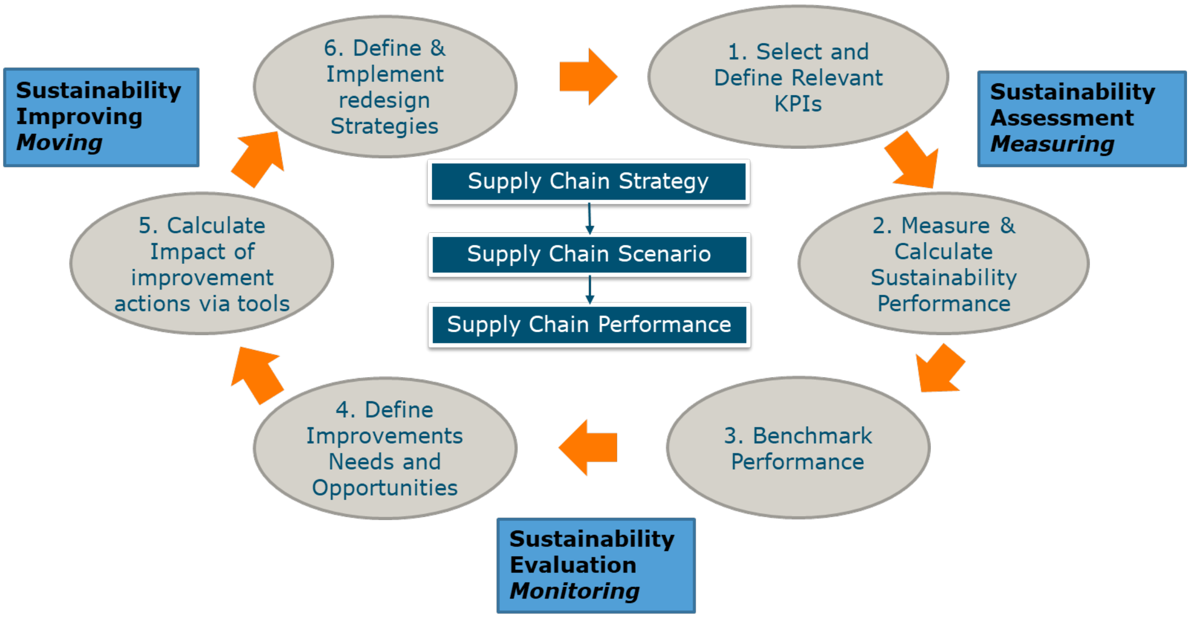


Figure 17: The Sustainable Logistics Management Approach. Source: Bloemhof-Ruwaard (2015).

Different progress levels can be observed in each country or society; developed countries are entering the regenerating phase (BOSMAN; ROTMANS, 2016), while the less developed and underdeveloped countries are still striving to reduce degeneration. In both cases, economic development and environmental degradation are yet to be completely decoupled, due to e.g. technological and/or economical restraints. Countermeasures like environmental impact minimisation are still required until full integration between humans and nature is achieved (BORLAND; LINDGREEN, 2013). In the next subsection, Sustainable Supply Chain Design, is reviewed under the perspective of the path towards ecocentrism.

3.1.2 SUSTAINABLE SUPPLY CHAIN DESIGN

From the theory of Logistics Management, Bloemhof-Ruwaard (2015) defined a stepwise approach to develop sustainable supply chains, trying to address the challenge of achieving zero-waste, zero-emissions supply chains. The approach is represented in Figure 17, shaped around three phases: *Assessment*, where the supply chain's sustainability level is determined; *Evaluation*, focused on benchmarking the desired level to be achieved, and *Improving*, where the current supply chain is redesigned, moving it from the current to the desired state, balancing environmental, social and economic performances.

Sustainable principles have been incorporated in the Supply Chain (SC) Design process (ESKANDARPOUR et al., 2015). Table 3 describes the evolution in the field of sustainable supply chain design. Integrating environmental thinking within the supply chain

	Green SC	**Eco-efficient SC**	**Eco-effective SC**
Concepts	Environmental Integration	Eco-efficiency	Eco-effectiveness
General Purpose	Improving ecological efficiency	Improving ecological and economic efficiency	Improving system effectiveness
Main Idea	Integrate environmental thinking	Zero waste emission, zero resource use and zero toxicity	Positive Externalities
Focus	Environmental Awareness	“Doing things right" for the environment	“Doing the right things" for the environment
Design approach	Eco-innovation	Cradle to grave design	Cradle to Cradle design
Supply Chain Type	Open and closed loop supply chain	Open and closed loop supply chain	Closed loop supply chain
Waste Management	Reverse Logistics	Reduce, Reuse, Recycle	Upcycling*
Key Process Indicator	CO_2, eco-indicator*, etc.	Triple bottom line Indicators	Triple top line indicators

Table 3: Evolution of Sustainable Supply Chain Design. Based in Burchart-korol et al. (2012).

design is the main concept of the Green Supply Chain (SRIVASTAVA, 2007). These SCs had their ecological efficiency improved through e.g. decreasing the emission of GHGs after eco-innovations, leading towards an increase of the stakeholder’s environmental awareness. It also marked the adoption of reverse logistics practices to reintroduce waste back into the production chain.

With the introduction of the eco-efficiency approach, the focus shifted towards improving the environmental performance of the chain while keeping profit levels maximised - a “multi-objective” purpose. This supply chain generates less waste since it aims for zero-waste, “doing things right” for the environment through recycling processes under the linear paradigm of cradle-to-grave. Indicators that reflect the triple-bottom line performance of the chain are monitored, in the environmental, economic and social dimensions - with the highest weight given to the economic dimension. The last Supply Chain type in the Table is the Eco-effective, where closed loops are an inherent feature, and which purpose is to improve systemic effectiveness through cradle-to-cradle design. Waste management is performed for upcycling*, where a small amount of energy is required to reintroduce the waste in the production chain, generating positive impacts that are measured through triple top line indicators, more value-oriented.

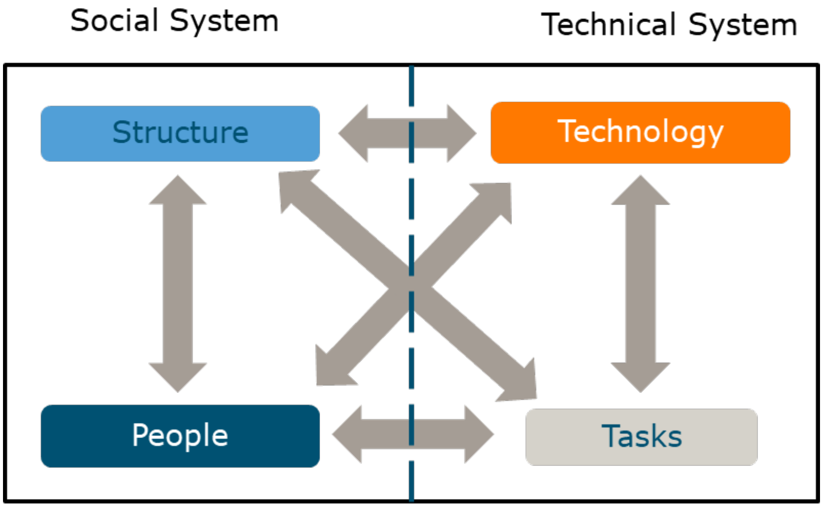


Figure 18: A depiction of a Socio-Technical System.
Source: adapted from Bostrom e Heinen (1977).

A summary of the findings from recent literature can be found in Appendix B. Main concepts used in each research and a brief description of the main findings are described. In the next subsections, concepts related with *what* was used in the process are reviewed, starting from the Socio-Technical and Socio-Ecological views, in the next subsection.

3.1.3 THE SOCIO-TECHNICAL AND SOCIO-ECOLOGICAL VIEWS

There are two schools of thought to depict societal systems, both featuring complex, dynamic, multi-scale and adaptive* properties (SMITH; STIRLING, 2010): the Socio-Technical System (STS) and the Socio-Ecological System (SES). The STS was defined in Bostrom e Heinen (1977), and is structured in four interdependent, interacting elements. Structure and People (forming the Social System) and Technology and Tasks – that together form the Technical System. Figure 18 presents this structure, aimed at supporting designers to consider every aspect or system dimension during the design process. Two-way arrows symbolise interactions among elements.

The SES view is composed of a ‘bio-geo-physical’ unit and the actors and institutions related with it (GLASER et al., 2008). A SES is delimited by spatial boundaries – not too small that no detail is perceived neither too big that will mask its emergent* properties (OSTROM, 2009). Figure 19 presents the SES framework as an unit of analysis. It is composed of Resource Units (e.g. lobsters), Resource Systems (a lake), Users (fishermen) and Governance System (organisations and rules governing fishing) (OSTROM, 2009). Again, two-way arrows describe interactions between elements, while the system interacts with other ecosystems, and social, economic and political settings. One of the primary concerns of the SES view is Resilience,

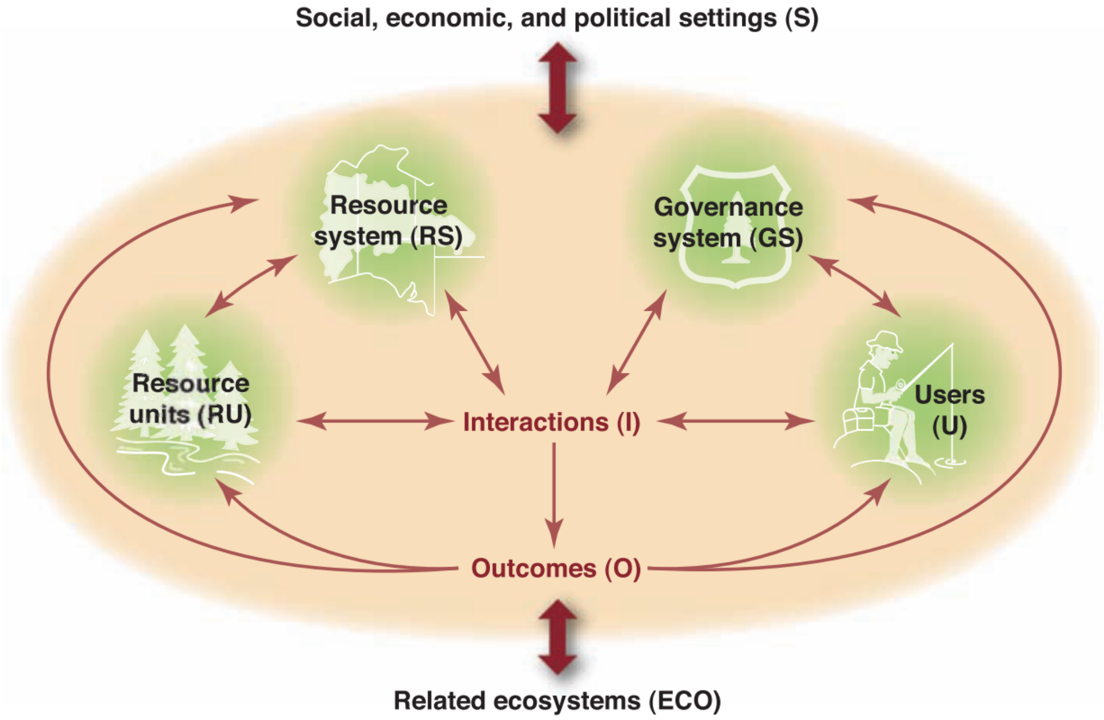


Figure 19: The Socio-Ecological System Framework. Source: Ostrom (2009).

defined as “the capacity of a system to absorb disturbance and reorganise while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks.” Walker et al. (2004). A SES shall not be explored in such a way it cannot recover, with the risk of becoming permanently damaged.

The SES and the STS views can be understood as different perspectives of a same system. Smith e Stirling (2010) argues that the main differences between both views are that (i) SES considers technology as an exogenous factor, as it already entails enough complexity from ecological and social systems; (ii) the SES view is place-bounded, while a STS can extend itself through more than one location (SMITH; STIRLING, 2010). Figure 20 represents the evolution of the integration of systems using both views. In the top left, the SES is in a central perspective, merging with the STSs it nestles, and all systems that are resilient transform into a new, alternate state. In the bottom right, the STS is in a central perspective, and it interacts with multiple SESs – as is the case of a supply network -, and they merge into a transformed, more sustainable system.

Conceived to be a regenerative system, the Circular Economy is reviewed in the next section.

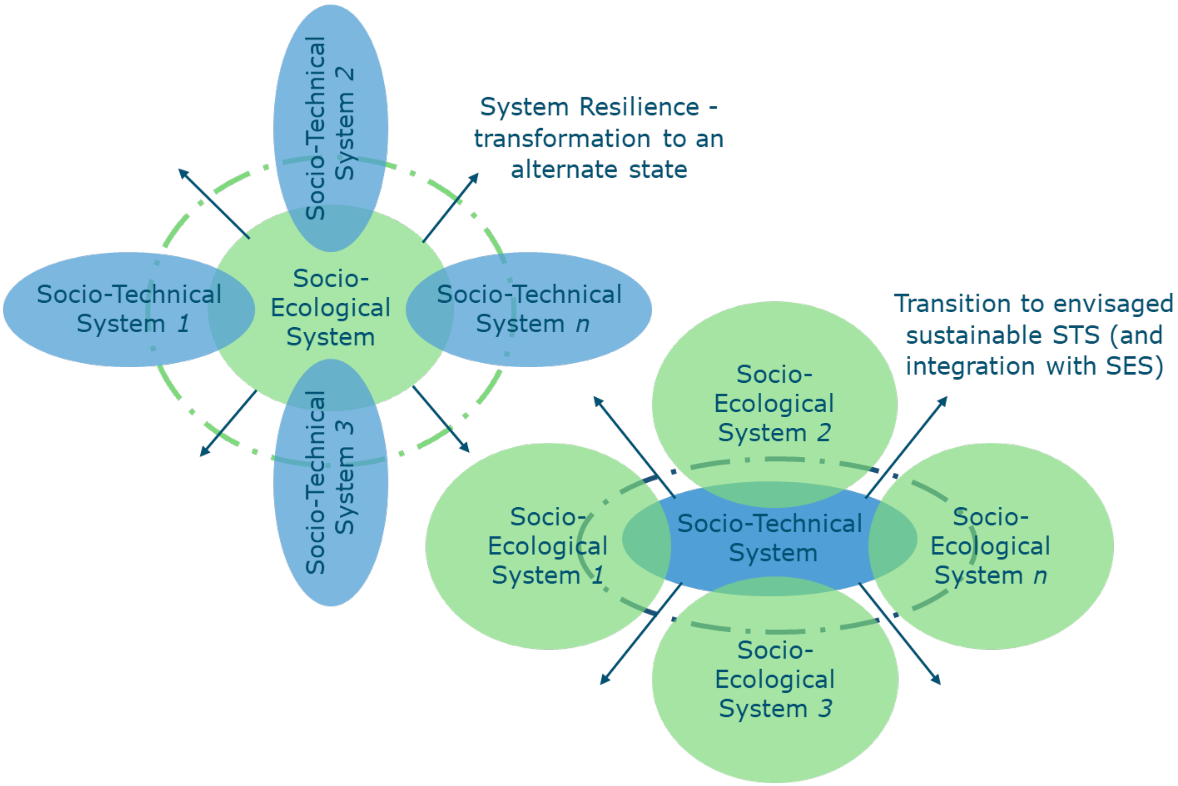


Figure 20: Integration between the SES and the STS views.
Source: adapted from Smith e Stirling (2010).

3.1.4 CIRCULAR ECONOMY

Intensively explored by the scientific community (SU et al., 2013), the Circular Economy (CE) has its origins in Pearce e Turner (1990), featuring multidisciplinarity, e.g., eco-efficiency, eco-effectiveness, cradle-to-cradle* design (BRAUNGART et al., 2007), Industrial Ecology (PECK, 1996). A recent definition was proposed by Geissdoerfer et al. (2017):

> "Circular Economy is a regenerative system in which resource input and waste, emission, and energy leakage are minimised by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling."

The degenerative open-loop, Linear Economy system of take, make and dispose must evolve to a closed-loop, regenerative, Circular Economy (GEISSDOERFER et al., 2017). CE is based in the RESOLVE framework, which stands for REgenerate (shift to renewables, restore ecosystems), Share (assets, prolong lifecycle), Optimise (increase performance/efficiency), Loop (closed-loop), Virtualise (dematerialise) and Exchange (Ellen MacArthur Foundation, 2015). Figure 21 illustrates the three main principles of CE: Principle 1 - Enhance and preserve natural capital by controlling finite stocks and balancing renewable resource flows.

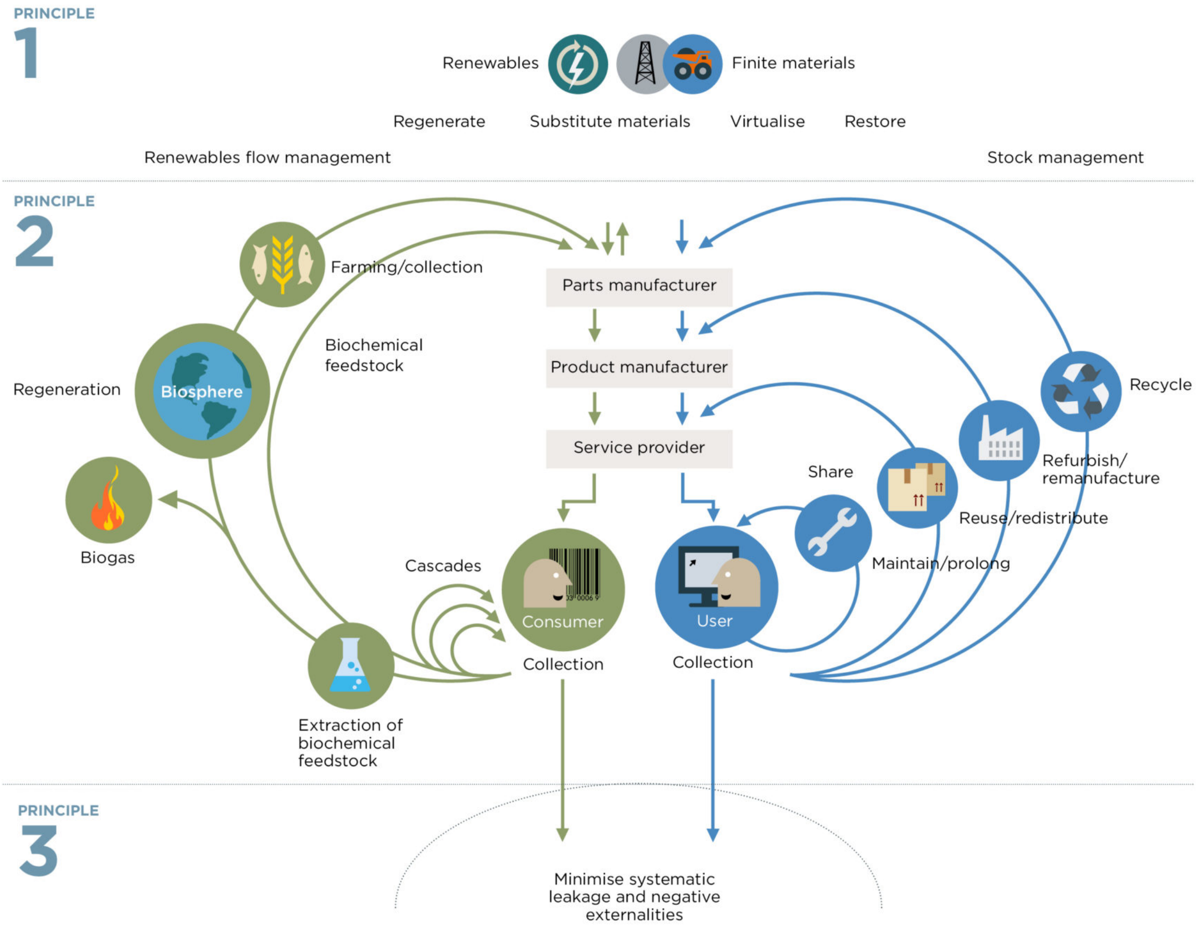


Figure 21: The Circular Economy model. Source: Ellen MacArthur Foundation (2015).

Principle 2 - Optimise resource yields by circulating products, components and materials in both the biological cycle (where organic elements circulate) and the technological products cycle. Principle 3 - Foster system effectiveness by revealing and designing out negative externalities*, regarded as "leakages" of the closed-loop system.

In this research, the adoption of a systemic view over the Supply Chain implies approaching it as a Supply Network and accounting for its resilience; both subjects are reviewed in the next subsection.

3.1.5 SUPPLY CHAIN AS A COMPLEX SYSTEM: THE SUPPLY NETWORK

The increasing complexity of Supply Chains demands a more appropriate approach than linear chains: the complex networks approach (CHRISTOPHER; PECK, 2004). An organisation should manage both the active and the inactive members, characterising the Supply Network (SN), defined in Braziotis et al. (2013):

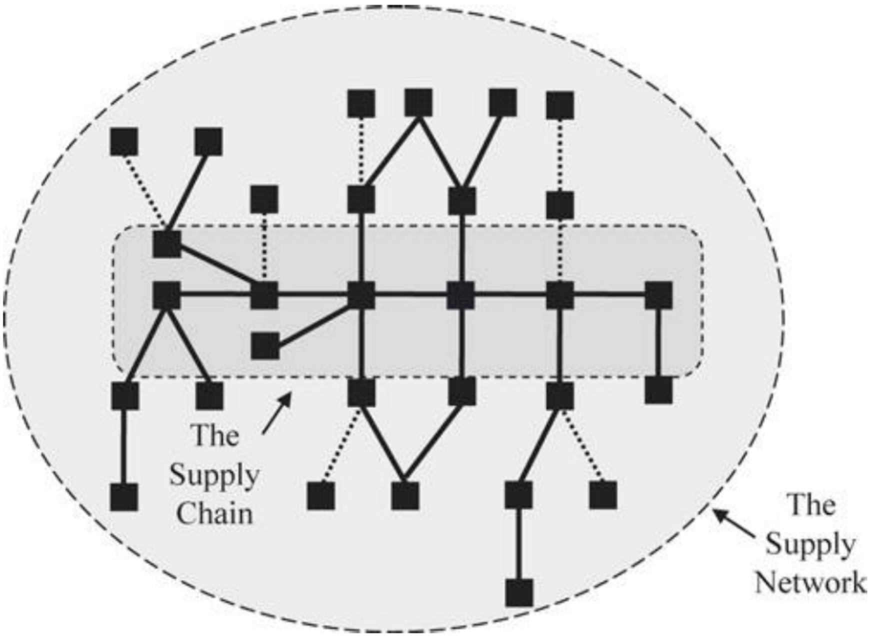


Figure 22: The Supply Chain and the Supply Network. Source: Braziotis et al. (2013).

> “[. . .] a set of active members within an organisation’s supply chains, as well as inactive members to which an organisation relates, that can be called upon to actively contribute to a supply chain if a need arises.”

Figure 22 illustrates the difference between active members – nodes connected with solid lines -, and inactive members - nodes connected with dashed lines. The Supply Chain formed by the active members is highlighted in the central square, with the outer circle encompassing the supply network.

Supply networks can be framed as Socio-Technical Systems (BEHDANI, 2013), i.e., as “complex physical-technical systems and a network of interdependent actors” (BRUIJN; HERDER, 2009). A supply network is composed of, e.g., facilities, reprocessing companies, transporters, which are nested socio-technical subsystems, interrelated in social networks. Overall, its behaviour is an outcome of the interactions within the networks and the interactions and interdependence among systems, which influences, among other characteristics, their adaptiveness, or their ability to change behaviour (BEHDANI, 2013, p.89-93) to cope with disruptions.

Disruptions are “random events that cause a supplier or other element of the supply chain to stop functioning, either completely or partially, for a (typically random) amount of time.” (SNYDER et al., 2016). Handling disruptions without losing function is achieved with Resilience, an emergent property considered vital for sustainable systems (CHOPRA; KHANNA, 2014). Research on Supply Chain resilience can be classified in two types:

handling disruptions, or developing mitigation strategies (SNYDER et al., 2016). For the first type, Fahimnia e Jabbarzadeh (2016) used Operations Research techniques to model the resilience performance of a supply chain by maximising its performance for both stable and disruptive scenarios. Through a stochastic fuzzy goal programming approach, they optimised the configuration of a supply chain that meets delivery demands in both scenarios, with minor penalties in operation cost and sustainable performance.

Mitigation strategies have been approached through disciplines like Management and Network Science. Christopher e Peck (2004) grouped disruptions in three types: internal to the firm (related production processes and control), external to the firm but within the network (caused by variation in Demand and/or Supply) and external to the network (from Environmental causes). They defined the resilient supply network through four general principles: (i) resilience should be designed in; (ii) corporations involved in the network must collaborate, (iii) a network must be agile and (iv) a risk management culture should be fostered.

During the design of a network, principles that enhances organisation's resilience must be accounted for by the designer, reducing the likelihood and severity of disruptions in the network (MARI et al., 2015). Pettit et al. (2013) listed 21 vulnerability and capability factors that influence supply chain resilience. Vulnerability factors are turbulence, external pressures, resource limits, sensitivity, connectivity and supplier/customer disruptions. In Table 4, six main vulnerabilities and capabilities factors are listed, based in the ranking of priorities developed in that research.

Network Sciences approach implies using complex systems theory to develop mitigating strategies. Mari et al. (2015) compared different strategies to model networks when simulating disruptions, investigating the behaviour of resilience metrics accessibility, robustness, flexibility and responsiveness. Levalle e Nof (2017) extended the study to supply networks, dividing it in three layers - the flow network, agents and the communication network – two dimensions: structure (topology and resources) and control protocols – and two levels, agent and network level. They also highlight that previous research suggests an interdependence between resilience and sustainability, from the combination of resource use, current vs. opportunity costs, and short vs. long term effects.

From the field of Ecological Economics, the Ecosystem Network Analysis (ENA) has been proposed as a measure for resilience, and is reviewed in the next subsection.

Type	Factor	Definition
Vulnerabilities	Connectivity	Degree of interdependence and reliance on outside entities
	External Pressures	Influences, not specifically targeting the firm, that create business constraints or barriers
	Resource Limits	Constraints on output based on availability of the factors of production
	Sensitivity	Importance of carefully controlled conditions for product and process integrity
	Supplier/Customer Disruptions	Susceptibility of suppliers and customers to external forces or disruptions
	Turbulence	Environment characterised by frequent changes in external factors beyond your control
Capabilities	Collaboration	Ability to work effectively with other entities for mutual benefit
	Capacity	Availability of assets to enable sustained production levels
	Flexibility in Sourcing	Ability to quickly change inputs or the mode of receiving inputs
	Flexibility in Order	Ability to quickly change outputs or the mode of delivering outputs
	Adaptability	Ability to modify operations in response to challenges or opportunities
	Anticipation	Ability to discern potential future events or situations

Table 4: Vulnerability and Capability Factors of an Enterprises Resilience.
Source: Pettit et al. (2013).

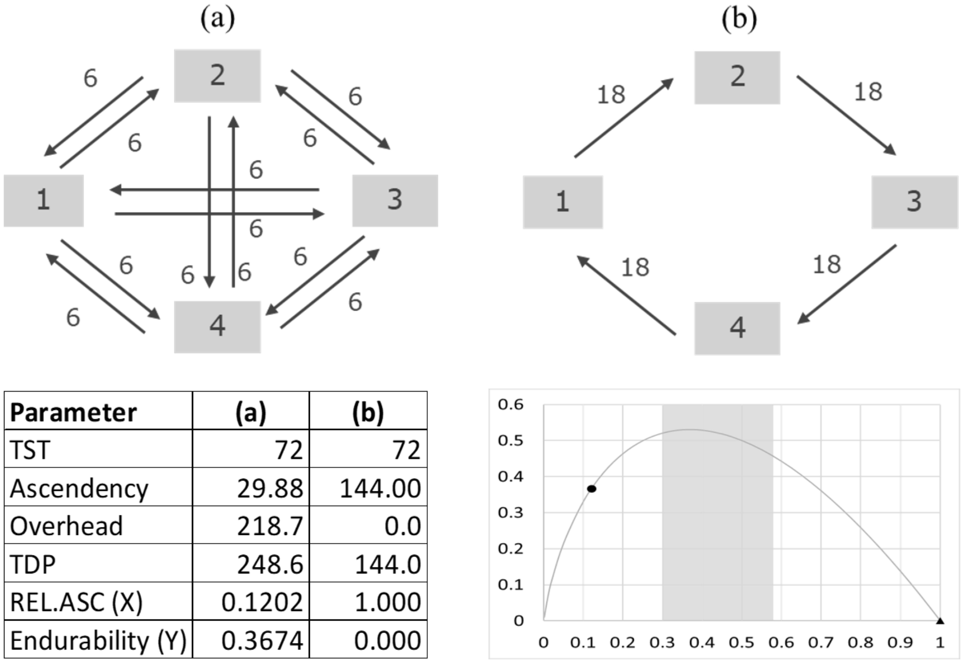
Property	Description	Equation
total system throughput (TST)	Sum of the flows within the system	$T_{..} = \sum T_{ij}$
Ascendency	Fraction of medium that an ecosystem distributes through regular, orderly and coherent routes	$A = \sum T_{ij} \log\left(\frac{T_{..}T_{ij}}{T_{i.}T_{.j}}\right)$
Overhead	A measure of incoherent, irregular flows; system's potential to recover from perturbation	$\Phi = -\sum T_{ij} \log\left(\frac{T_{ij}^2}{T_{i.}T_{.j}}\right)$
Capacity (TDP)	Maximum potential that a system has at its disposal for development.	$TDP = A + \Phi$
Relative Ascendency (α)	Ratio between Ascendency and Capacity	$\alpha = \frac{A}{C}$
Robustness (E)	"Maximum fitness for evolution"	$E = -k\alpha\log(\alpha)$

Table 5: ENA concepts and equations.

3.1.6 ECOSYSTEM NETWORK ANALYSIS

The Ecosystems Network Analysis (ENA) is an analytic model based on information theory, formulated to quantify effective performance and reserve capacity of ecological ecosystems (ULANOWICZ et al., 2009). Lately, it has been argued that ENA outputs can be linked with the resilience performance of a technical system, e.g. supply chains Ulanowicz (2009), Li e Yang (2011), Goerner et al. (2015). Allesina et al. (2010) used it to evaluate the complexity of a supply chain before and after performing strategical changes. The definition of ENA used in this research is from Ulanowicz (2000), Ulanowicz et al. (2009). ENA concepts and equations are summarised in Table 5. Total System Throughput ($T_{..}$) is the sum of all the flows within the system - T_{ij} -, where i and j represent "compartments" exchanging flows, i.e., suppliers, customers.

Ascendency can be understood as a measure of how constrained the system is, and Overhead as its degree of freedom (KHARRAZI et al., 2017). $T_{i.}$ is the sum of all flows leaving i to any other company, whereas $T_{.j}$ is the sum of flows arriving at compartment j. In this research, base 2 is used for the log functions in the ENA equations from Table 5, following the same base used for Shannon entropy. Capacity is the total development power of a system – the sum of Ascendency and Overhead. Relative Ascendency is the ratio between Ascendency and Capacity, also called as Degree of Order (LAYTON, 2014). Robustness is defined as an ecosystem's ability for evolution. Its value is defined from Relative Ascendency, where k is a scalar constant, typically assuming the value of 1 for information theory practices (ULANOWICZ, 2000). If Ascendency is too low, the system may not survive due to the lack of internal organisation, or extent of activity. In the other hand, too little Overhead means the



Parameter	(a)	(b)
TST	72	72
Ascendency	29.88	144.00
Overhead	218.7	0.0
TDP	248.6	144.0
REL.ASC (X)	0.1202	1.000
Endurability (Y)	0.3674	0.000

Figure 23: Interpreting systems with ENA. Source: Battini et al. (2007).

system is too constrained, and therefore, too fragile to cope with disturbances (ULANOWICZ et al., 2009).

Concepts from ENA can be matched with system performance and resilience. Goerner et al. (2015) suggests that Overhead could be regarded as a measure for Resilience, naming Ascendency as “systemic efficiency” and Capacity as “network sustainability”. Kharrazi et al. (2017), in a similar way, calls Ascendency as Efficiency, but Overhead as Redundancy and Robustness, “Theoretical Resilience”. From this point onwards, nomenclatures Ascendency and Overhead are kept; to avoid confusion with production capacity, ENA’s Capacity is called *Total Development Power* (TDP). With the same purpose, Robustness will be called *Endurability* - “The quality of being suitable to fulfil a particular role or task” (Oxford Dictionary, 2018).

Figure 23 presents an example of a model application, comparing two types of systems; (a), highly interconnected, where every compartment relates to the others and (b), very specialised, where each compartment is connected only to another one. In the bottom left corner, a table presents the performance of both systems in terms of ENA’s six metrics. Results for TST are equal for both configurations, i.e., the they feature the same quantity of flows. As system (b) is more specialised and less interconnected, its Ascendency is significantly higher than of system (a), 144 against 29.9. On the other hand, system (a) performs better in Overhead (219), while (b) scores zero. If any connection of system (b) is broken, the flow is interrupted, which would not happen to system (a), as alternate flow channels could be used.

TDP for system (a) is higher than (b), as system (b) scores 1 in Relative Ascendency for being extremely specialised, therefore scoring zero in Endurability, meaning it struggles to cope with disturbances. A smaller *REL.ASC* means a better Endurability to system (a). Both results are plotted in the graph in the lower right part of Figure 23; α is plotted in the X-axis, while Endurability (E) is the Y-axis. The results of both systems place them outside the Window of Vitality (WoV) – the grey rectangle in the middle of the lower right graph in Figure 23, defined by the range $0.3 \leq \alpha \leq 0.58$ (LAYTON, 2014). In Ulanowicz (2009), it was observed that ecosystems tend to operate with maximum fitness for change if their performance remains within this interval. Systems operating within the WoV supposedly hold overhead enough to cope with disturbances and enough ascendency to perform well under stable environments.

In the next section, the methodology is presented.

3.2 METHODOLOGY

In this section, *how* the RSND development process was performed is described, starting with Transdisciplinary Research and ending with the artefact development methodology, Design Science Research Methodology (DSRM).

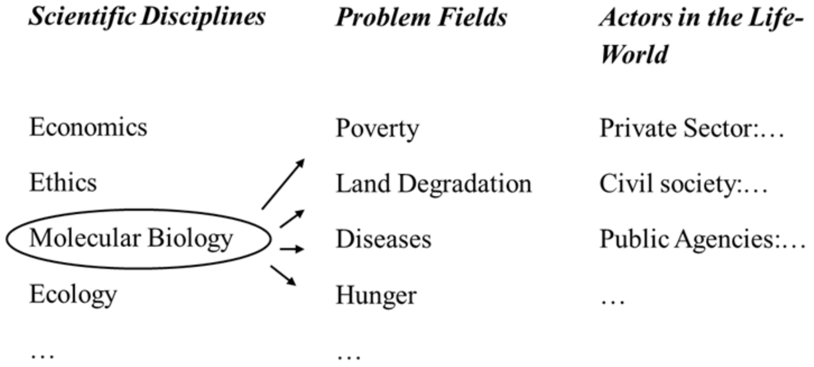
3.2.1 TRANSDISCIPLINARY RESEARCH

Transdisciplinarity is defined in Bergendahl et al. (2018) as “the incorporation of a broad set of scientific and policy disciplines, including industries and actors, for addressing broad and complex problems, e.g. sustainability.” TR is a more integrative research approach, capable of transforming sustainability into a concrete realisation rather then just a far objective, which cannot be accomplished by any discipline alone Mauser et al. (2013), Brandt et al. (2013). TR is recognised as appropriate to:

- “grasp the complexity of problems;
- take into account the diversity of life-world* and scientific perceptions of problems;
- link abstract and case-specific knowledge, and;
- develop knowledge and practices that promote what is perceived to be the common good” (POHL; HADORN, 2007, p.20).

Figure 24 summarises the differences between disciplinary (a) and transdisciplinary research (b). In the left part, examples of scientific disciplines are listed; at the centre,

(a) Disciplinary Research



(b) Transdisciplinary Research

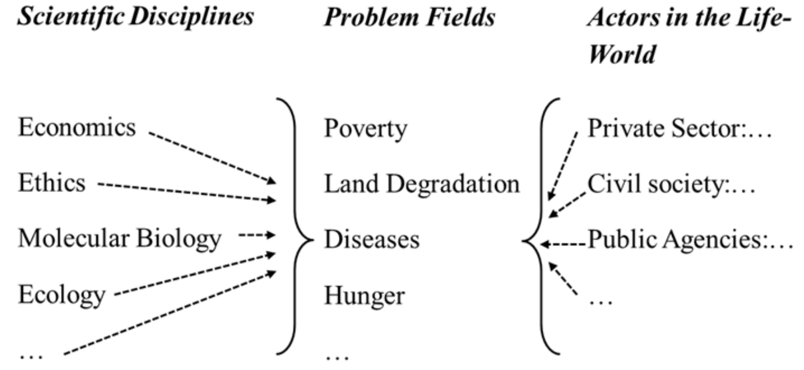


Figure 24: Disciplinary and Transdisciplinary Research compared.
Source: adapted from Hadorn et al. (2006).

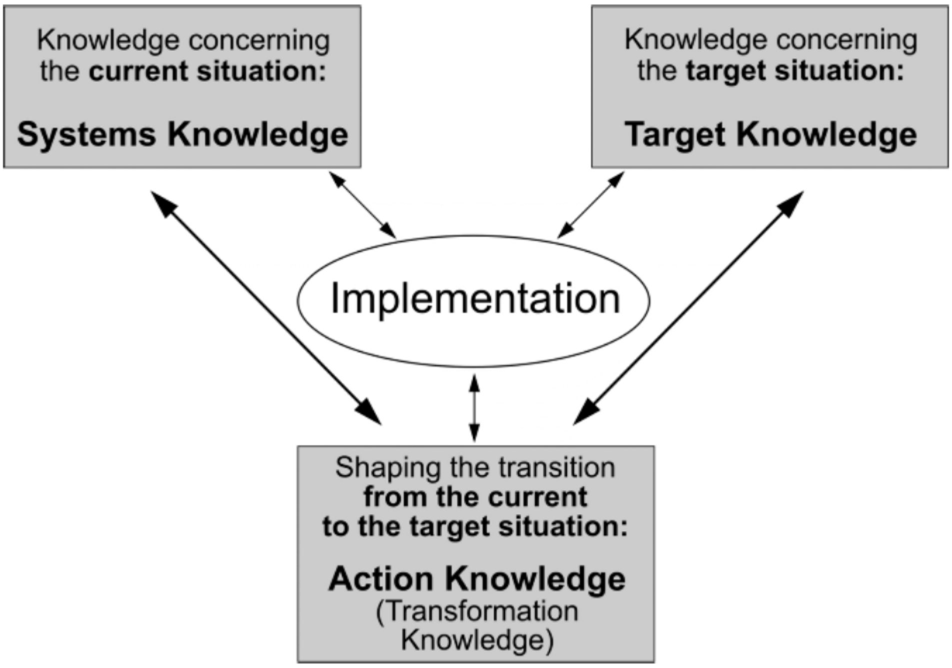


Figure 25: Types of knowledge associated with TR. Source: Hadorn et al. (2008), p.59.

some of the current problem fields* faced by mankind and, to the right, actors that deal with these problems in a daily basis. Disciplines are important in the search for solutions in any problem field; that is represented by the arrows in (a). However, the arrows' tips do not come close to the problem fields due to the inherent impossibility of grasping a problem's entire complexity (HADORN et al., 2008, p.34). Actors are not directly connected, although they have expectations about the research outcomes. In (b), TR surpasses the boundaries between disciplines, merging knowledge bases in a less defined shape. Both scientific and practical knowledge can be applied, what is represented by the dashed arrows from all the disciplines and actors in the list towards the problem field, e.g. diseases. Initially, any discipline or actor can be a source of knowledge for a certain problem field, with the brackets representing their integration Hadorn et al. (2008).

Figure 25 represents the three types of knowledge produced with TR. Systems Knowledge is acquired when systems are investigated on their current function and behaviour through theory-driven research. Target Knowledge is produced when an ideal future situation is proposed. Action (Transformation) Knowledge is produced when the research focus is on the transformation of existing practices, or on the introduction of new ones within the technical, social and cultural dimensions Hadorn et al. (2008). Target and Transformation knowledge are acquired with problem-driven research.

In the next subsction, DSRM is reviewed.

3.2.1.1 DESIGN SCIENCE RESEARCH METHODOLOGY

Design Science Research Methodology (DSRM) gives support to prescriptive research – where artefacts* are proposed to solve scientific problems (AKEN, 2004). Figure 26 illustrates the iterative procedure to develop the RSND procedure, based in Peffers et al. (2007). The circle represents the entry-point to develop the artefact, an objective-centred input: supply networks regenerate ecosystems, reverting environmental damage. The methodology consists of six activities, each one represented in a box: Identify the problem and motivate, define objectives for a solution, design & development, demonstration, evaluation and communication. The three first activities are described in this section. The boxes of Demonstration and Evaluation, in the dashed boxes, are described in chapter four, while Communication is a continuous activity, and summarised in chapter five.

From the main objective, the problem and objectives for the solution are defined: resource depletion and the degradation of ecosystems are problems that can be solved if supply networks regenerate the environment. The problems identified are complex, as they relate with sustainability; therefore, the need for TR is evaluated answering the three questions pointed in Hadorn et al. (2008, p.34):

- Knowledge about a relevant problem field is uncertain: little is known about how interactions occurring within the supply networks, or between the supply networks and the surroundings, influence environmental degeneration. It is unknown how to design regenerative supply networks;
- The concrete nature of problems is disputed: there is a considerable number of solutions to improve a supply chain's environmental performance, through e.g., (i) optimising eco-efficiency, (ii) weighting of environmental indicators and (iii), defining resilience with multiple dimensions, or quantifying it. The regeneration of ecosystems has not been explicitly expressed as a target, while resources continue to be depleted and ecosystems degraded, suggesting that the concrete nature of the problem requires a more integrated, purposeful design approach;
- There is a great deal at stake for those concerned by the problem: resource depletion and ecosystems degradation endangers the continuity of the human species in a global level; in the local level, actors involved within the network are impacted; in the regional level, ecosystems interacting with the network, neighbouring companies and neighbourhoods.

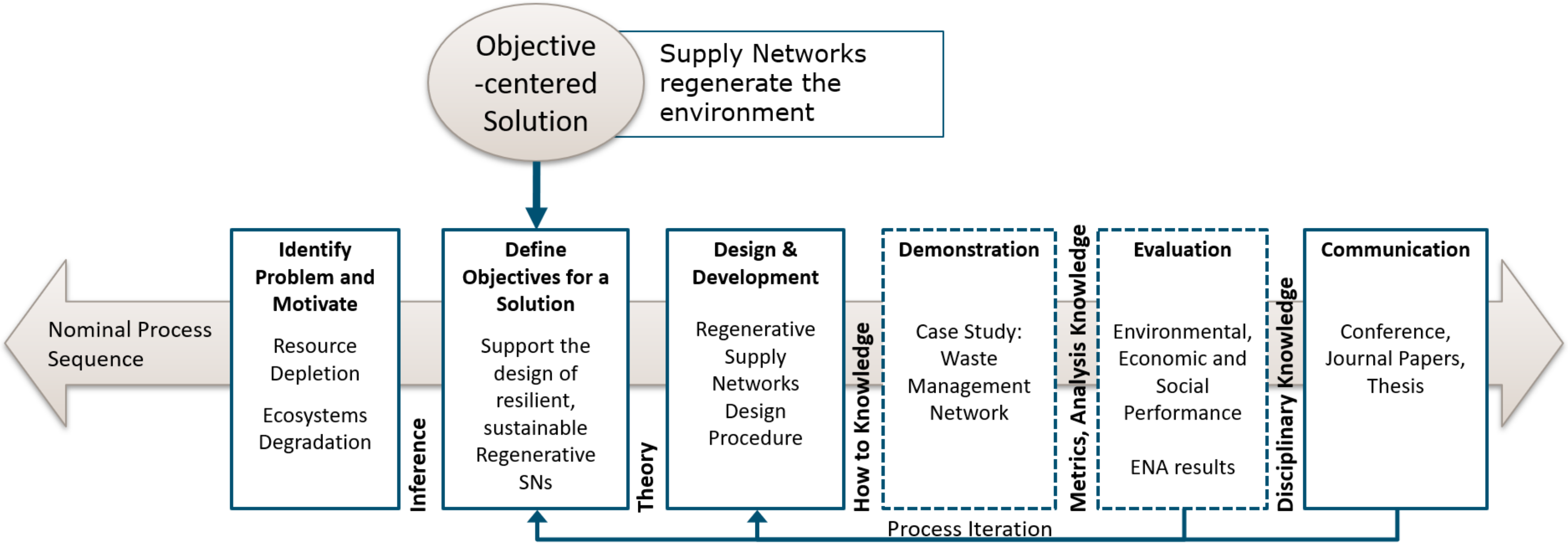


Figure 26: Research Methodology. Source: adapted from Peffers et al. (2007), Dekkers (2017).

Activity 2, objectives for a solution, requires characterising the ultimate artefact: the Regenerative Supply Network (RSN). Based in the framework of Burchart-korol et al. (2012), the RSN is outlined in Table 6. Principles of purpose and “the common good” from TR are aligned with the ecocentric perspective: the *common good* is *environmental regeneration*, the purpose driving the RSN design process, which therefore should be the at the start of the design process. Through network resilience, the RSN can cope with disturbances and endure, delivering environmental benefits in the long term. An objective for the solution becomes supporting the design of regenerative supply networks that feature sustainable performance in the three dimensions, and resilience to deploy regeneration in the long term.

The main idea is that the SN contributes with the reversion of environmental degradation identified in the surroundings where it operates. The SN is focused in “doing the right things right”, i.e., combining eco-effectiveness and eco-efficiency approaches, maximising benefits and minimising eventual environmental impacts. Eco-effective design approaches are biomimetic, upcycle design, and RESOLVE, from Circular Economy. The supply network type is based in closed-loop networks formed through collaborative relationships and CE, regenerative by definition. The waste management in a RSN is performed following the 6R hierarchy, in order of priority: reduce, reuse, recycle, recover, redesign and remanufacture. Finally, Key Process Indicator (KPIs) should be selected according to the regeneration type, system inputs and outputs, and interactions between the SN and the surroundings. KPIs should reflect the gains achieved in the sustainability dimensions, with positive results.

Activity 3, Design & Development, requires a definition for the RSN design process. Different concepts related with the artefact were merged accordingly. A procedure for the design process is proposed, based in Bloemhof et al. (2015). The design process should start with the activity of defining which is the regenerative purpose of the SN. Such definition impacts the SN’s input and output flows, which must be defined using one of the eco-effective design approaches listed in Table 3. After defining the flows, the RSN can be conceptualised, depicting its interactions with the surroundings, defining the transformation processes, locations, facilities and flow allocation. Resilience principles reviewed in Table 4 are used during the conceptualisation of the network. The conceptual system can be converted in a mathematical problem, that can be optimised in terms of economic, environmental and social performance. Multiple network configurations are outputted by the model, each with a different performance balance among the three dimensions, using metrics related with the SN context - the repositories in Singh et al. (2009), Rodrigues et al. (2017) can guide the choice of the metrics.

	Regenerative	**Comments**
Concepts	Transdisciplinarity, Regenerative Design and Network Resilience	A more effective way of addressing problems – resilience allows the SN to cope with disruptions* and endure
General Purpose	Restore/Regenerate the environment	The "common good" proposed in this research
Main Idea	Revert environmental degradation	Understanding the regeneration needs of the interacting SESs
Focus	Doing the right things right in the long-term	Combining eco-effectiveness, eco-efficiency and resilience
Design approach	Biomimetic; Upcycle; RESOLVE	Flows can be designed through these design techniques
Supply Chain Type	Closed-loop Networks; Circular Economy	Supply Networks instead of supply chains; CE is by definition, regenerative
Waste Management	6R	Priorities for end-of-life destination: reduce, reuse, recycle, recover, redesign, remanufacture.
Key Process Indicator	Context-related, stressing benefits achieved	Indicator(s) must communicate gains in the three sustainability dimensions

Table 6: The Regenerative Supply Network Outline.

The design & development DSR procedure is iterative until coherence is achieved among the problem description, the objectives defined for the problem and the designed artefact – does it effectively implement the solution objectives? When these questions are properly answered, the artefact is finished. In the next section, the RSND procedure is described.

3.3 RESULTS

The Regenerative Supply Network Design definition follows, merging the concepts of supply networks (BRAZIOTIS et al., 2013), supply chain design (MELNYK et al., 2014), Sustainable Supply Network Design (BALS; TATE, 2018), regenerative design (MANG; REED, 2012), systems approach (ACKOFF, 1994) and resilience (CHOPRA; KHANNA, 2014):

> "from a regenerative purpose, identifying the strategic outcomes for the supply network and developing, implementing, and managing the resources, processes, interactions and collaborative relationships (along the network and with the socio-ecological wholes) in the long term, ensuring optimal functionality, environmental, social and economic feasibility, while adapting to disruptions."

The regenerative purpose is the starting point of the definition, stressing the shift towards ecocentrism. Systems thinking is addressed with interactions, networks and socio-ecological wholes. Collaboration is the means through which value-oriented relationships are established (SEURING, 2013). “Optimal" recalls operational efficiency, while sustainability is accounted for with a long-term view in environmental, social and economic dimensions. Last, resilience is represented by *adaptability*, to cope with disturbances while retaining its function. The RSND procedure consists of four stages, illustrated in Figure 27: *Regenerative Purpose*, *Input-Output flows*, *System Conceptualisation*, and *Performance Optimisation*. Each stage is based in main principles as represented by the bullets under the main arrow. The thinner arrows around the main arrow represent that the procedure is recursive; one can go back and forth. Sustainable Performance Indicators are defined in the first three stages and used in the fourth stage for determining and measuring the optimal performance.

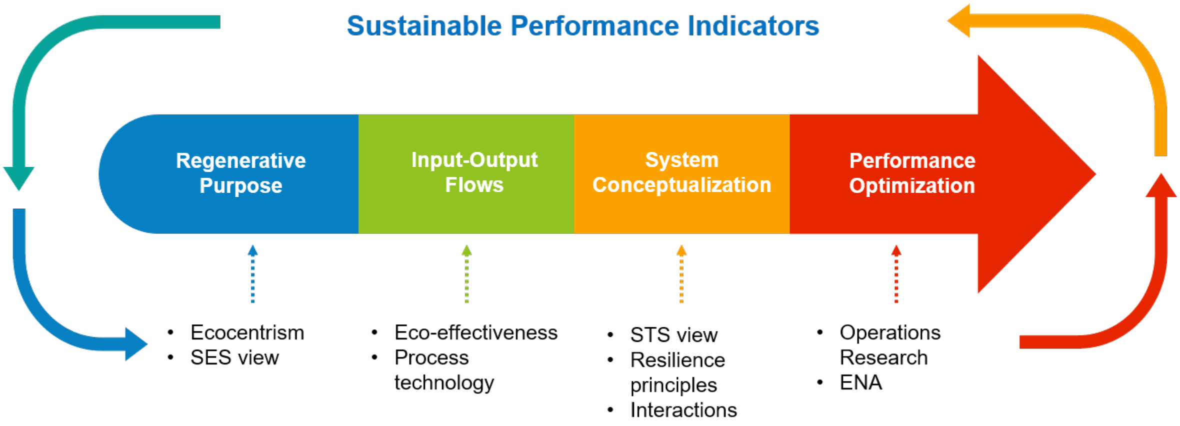


Figure 27: The Regenerative Supply Network Design Procedure.

The process begins with an ecocentric perspective: in the first stage, a purpose related with environmental regeneration is identified. Analysis of the surroundings under the SES view reveal opportunities in which the network can contribute, regarding environmental pressures, ecological configurations (e.g. how is the biodiversity of the SES?), resource units (renewable resources available?), ecosystem services* (water supply), wants and needs of its users, and local legislation and policies. Guidelines can be consulted during this analysis, like the Sustainable Development Goals - see Folke et al. (2016), Greenhouse gases emissions, or ocean contamination.

When a regenerative purpose that matches the network function is found, next stage concerns (re)designing the network’s inputs, outputs and process technologies linked with the purpose defined. From an eco-effective approach, biomimicry, upcycle, Industrial Symbiosis* - “waste equals food” -, or the RESOLVE framework can be evoked, if needed. Product outputs can be transformed in service outputs, in a product-service system* (PSS) configuration. As an

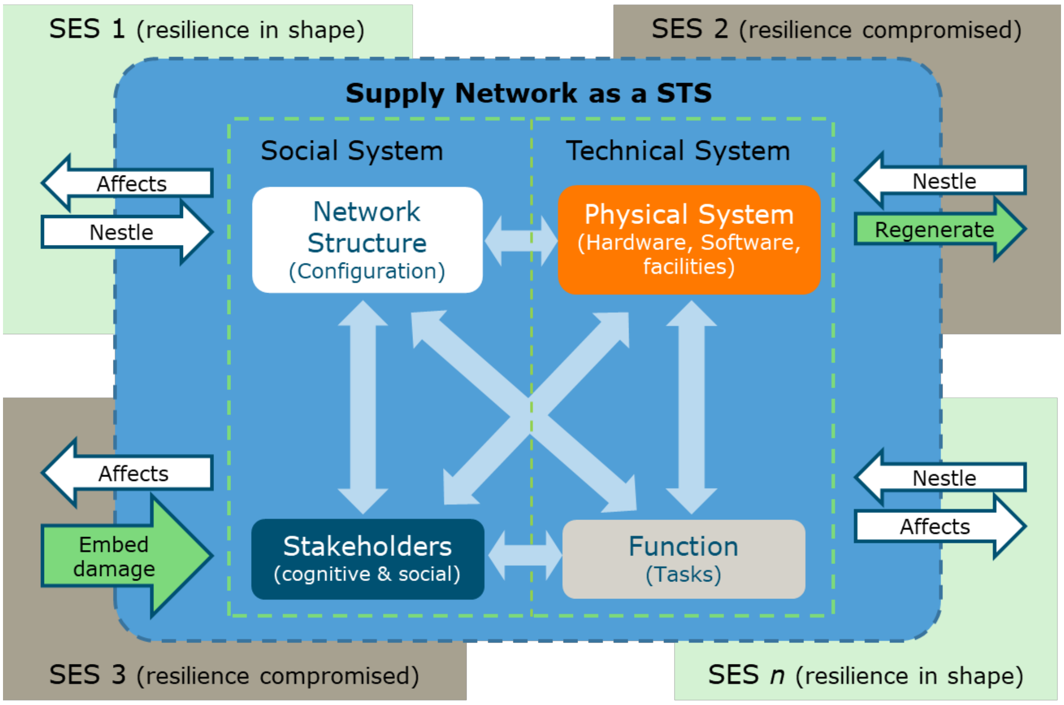


Figure 28: Interactions model among the regenerative SN and surrounding SESs. Source: based in Behdani (2013), Bostrom e Heinen (1977), Oosthuizen e Pretorius (2016), Smith e Stirling (2010).

example, if it is decided that a supply network of housing construction materials will engage on reducing ocean contamination, replacing raw materials like cement and minerals by plastic collected from the ocean could be the redesign strategy adopted. This implies on changing processing technologies involved, and outputs.

Selection of manufacturing processes are performed eco-effectively, seeking for the most environmental-friendly processes available. Such transformation implies on performing investments, which can be optimised in the fourth step. In the third step, the supply network system is conceptualised as a Socio-Technical System - represented in Figure 28. In the inner rectangle to the left, the Social System consists of the Network Structure, i.e., the configuration of active, inactive members and flow directions among the Stakeholders - the agents* involved in the network, e.g. suppliers, customers, transporters.

In the Technical System, the Physical System consists of goods being transported, hardware used for production processes, software (or soft systems) used for management and control, and facilities, like plants or warehouses. Finally, the box Function represents the tasks and function performed by the supply network. Arrows linking elements symbolise the interactions among them; e.g., a certain function will imply in tasks that influences the type of companies involved in the network, which in turn impacts the network configuration and the hardware used in the production process.

Figure 28 also depicts the interaction between the supply network and the surrounding SESs. The SN can interact with *n* SESs, absorbing damage performed to SES #3 – which ecosystem resilience is compromised -, while affecting it through e.g. transportation emissions. The SN is nestled within SES #2, performing tasks that regenerate that system. The SN also impacts SES #1, featuring resilient capacities, and such impacts should be minimised, while SES's #1 resilience should be monitored. Network resilience principles are used in this step to define some of the network requirements, like redundant suppliers and/or customers, multiple inputs and outputs, and the reserve capacity defined for the production processes. The output of the third step is a conceptual model, in the form of e.g. a flow diagram, which will be transformed in an optimisation model.

In the fourth stage, a mathematical model is developed based in the conceptual model built in stage three. A problem is formulated by the designer, and later optimised – e.g. location-allocation or vehicle routing problem. System features are translated into sets, parameters, variables and equations. Equations can be defined from eco-efficiency, eco-effectiveness and resilience: e.g., an objective function can minimise environmental impact, or a constraint can define a percentage of waste used as an input, or reserve capacity. The mathematical model is transformed into a computer optimisation model, solved through Operations Research techniques, prescribing the network configuration for an optimal economic, social, and environmental performance, using the indicators previously defined. Network configurations will indicate which suppliers are actively engaged, which are inactive, and which material flows are exchanged between companies. ENA is used to quantify the resilience of each configuration, and the outputs of Relative Ascendency and Endurability are used to evaluate which configuration features the most the balanced resilience.

3.4 DISCUSSION

In this chapter, the socio-ecological intergradation from Gruner e Power (2017), was explored to propose a design definition where the supply network is approached as a Socio-Technical System, defining environmental regeneration as the common good, and the starting point for the RSN design process. The RSND procedure adds on the scientific knowledge supporting practitioners (AKEN, 2004): through its adoption, companies engage in reverting degradation and restoring ecosystems, realising the transformation from the business-oriented, anthropocentric approach towards a system-oriented, ecocentric approach in the path towards regenerative development. The communication of positives instead of negatives – "the glass is half full" – increases motivation along the stakeholders involved (MCDONOUGH;

BRAUNGART, 2013, p.214). Defining context-based indicators to measure the performance enhances such communication: for example, if the purpose is linked with Greenhouse Gases (GHG) emissions, using net GHG savings (avoided minus emitted GHG by the system) gives a perspective of the gains achieved.

Using the procedure to guide the design process does not completely mitigate eventual unintended effects. However, if the purpose is ecocentric and regenerative, these unintended effects may probably be desired, and emissions can be “celebrated" (MCDONOUGH; BRAUNGART, 2013, p.217). For example, if landfills are recovered and transformed into recreational parks with the purposed of capturing GHG, the quality of life of the neighbours is also improved (SIMIS et al., 2016), as well as the quality of underground water (DANTHUREBANDARA et al., 2015), which in turn restores ecosystem’s resilience. Framing a SN around the three sustainable dimensions shift the primary focus on economic performance, meaning that profit will probably be compromised in favour of environmental and social performance. This can be regarded as a strong evidence of the shift from anthropocentrism to ecocentrism, where the meaning of value is transformed. The role of optimisation is fundamental to achieve network configurations that can deliver sustainable performance, handling trade-offs between sustainable dimensions (SEURING, 2013). It is as similar as performed in researches optimizing an eco-efficient frontier, but in this case, focus is given to maximisation of indicators that communicate positive outcomes.

Managing and balancing the trade-offs among conflicting features is key to achieve high performance levels in the SN. Evidence from Fahimnia e Jabbarzadeh (2016) points that environmental and social performance are not harmed by improving resilience, while Souza et al. (2019) argued that resilience may be harmed if optimisation focuses on minimising environmental impacts. In any case, both dimensions are interdependent Levalle e Nof (2017). Eco-efficiency is regarded as in opposition with eco-effectiveness, as they originated from different approaches, and may result on conflicting decisions regarding resource use. Mapping interactions between the SN, framed as a STS with its surroundings - framed as SESs -, allow for a more integrative design, linking product and supply chain design (JAYAL et al., 2010), understanding a problem and proposing solutions in multiple levels, as in Joore e Brezet (2015). The synthetic approach allows for an increased harmonious fitting of the SN in the environments it is nestled. A regenerative purpose means that the system is feeding itself from the SES while returning something back to it, in a mutualistic relation, realising the integration process proposed in Smith e Stirling (2010).

3.5 CONCLUSIONS

This research proposes a regenerative supply network design procedure based in Regenerative Development, Transdisciplinarity, Systems Approach, and Design and Social Sciences. A definition for RSND is proposed, and a design procedure was approached as an artefact developed using DSR methodology. The procedure consists of four stages, guiding the design of supply networks that fulfil its function and engage on environmental regeneration with a sustainable performance in the long term. The order in which concepts are introduced is based in ecocentrism: first, environmental regeneration, then eco-effectiveness, then systems approach and last, eco-efficiency. Resilience is deployed during the network conceptualisation and verified in the Performance Optimisation stage. In the fourth stage, the SN is modelled as an optimisation problem and solved, outputting network configurations and their respective sustainable performance.

The contributions of this chapter can be framed in the TR knowledge types. The identification of the environmental performance of the current SN in operation can be regarded as contribution for the Systems Knowledge. Through the SES view, it is possible to identify how the current SN interacts with its surroundings. The definition of a regeneration purpose for the SNs is a contribution in Target Knowledge. The target situation is based in the common good, where the SN engages in environmental regeneration and recovering ecosystem's resilience, merging with the SESs it interacts with. Transition Knowledge is generated from the identification of the progress towards regenerative development, and the intrinsic features of the supply chains progressing until there: green, eco-efficient, eco-effective and regenerative.

The scope of this research is limited to the design of the SN: the choice of the configurations and posterior implementation of the SN were not addressed in this research. Choosing the network configuration implies on decision-making by the stakeholders involved; economic, social, environmental performance and resilience should be considered. Multi-criteria Decision Analysis* (MCDA) techniques like weighting can be used, defining priorities among the indicators. The implementation of an SN can result in changes on the design definitions, altering the configuration proposed (SLACK et al., 2007, p.290). It is of utmost importance that the proposed design is not distorted, keeping track of its features and monitoring performance. The supply network design process can be improved in terms of transdisciplinarity, increasing the scope of the problem field to address other problems within the supply chain, in multiple levels. When approached from the problem perspective, reliable improvements can be achieved with the progressive integration of the research streams, improving the consistency of the solutions proposed. Last, demonstration and evaluation of the artefact are performed in chapter four, through the design of a Waste Management network.

4 A REGENERATIVE WASTE MANAGEMENT NETWORK FOR THE REGION OF NORTE PIONEIRO, PARANÁ

With the increasing environmental degradation leading to unprecedented consequences like ocean plastic patches and drastic global warming, there is an urgent need to perform actions that regenerate the environment (Ellen MacArthur Foundation, 2015; FULLERTON, 2015; HERRMANN et al., 2015; LODDER et al., 2014; REED, 2007), which can be performed in the micro-level of small regions or the macro-level of entire continents. One major problem related with this degradation is caused by inadequate solid waste disposal (DANTHUREBANDARA et al., 2015; CANNON, 2015).

In Brazil, the culture of take, make and dispose is predominant in waste management. More than 90% of all municipal solid waste (MSW) goes to dumping grounds, controlled landfills or sanitary landfills (Brasil, 2016, p.151), the least favourable option, according to waste hierarchy strategies Annepu (2012), EPA (2015), Wikipedia contributors (2018d). This situation is both environmentally and economic unsustainable, since governments face yearly losses from waste management activities (Brasil, 2016, p.116). With the increase of waste generation volumes due to population growth, sanitary landfills are becoming overloaded. As a result, the number of sites degraded by improper waste disposal is growing, increasing global warming, soil and water contamination (DANTHUREBANDARA et al., 2015).

Solutions for waste management problems involve the research stream of Integrated Municipal Solid Waste Management (IMSWM), showing beneficial effects in multiple dimensions: in the IMSWM system of Muangklang, Thailand, a reduction of 60% of net Greenhouse Gases (GHG) emissions was achieved (MENIKPURA et al., 2013). Normally, different waste management scenarios are compared, varying their strategy (LIU et al., 2017), comparing their financial sustainability achieved through different partnership models (LOHRI et al., 2014). The Circular Economy approach has also been explored to the design of waste-to-bioenergy IMSWM systems , minimising capital cost and GHG emissions, while maximising monthly profit (BALAMAN et al., 2018). Recovery of degraded sites - also called “brownfields” - has been studied in terms of the benefits in the quality of life of neighbours after the regeneration of urban landfills Simis et al. (2016), and in terms of Enhanced Landfill Mining, where landfill waste is mined and reintroduced in production chains through environmentally-friendly recycling and energy production processes Danthurebandara et al. (2015), Jones et al. (2013).

However, a waste management system that is designed around the purpose of environmental regeneration, with a sustainable performance and resilience, could not be found in the literature. In this Chapter, the Regenerative Supply Networks Design (RSND) procedure is demonstrated to design a Regenerative Waste Management Network for the region of Norte Pioneiro, Paraná, south of Brazil. The waste network system processes waste collected from 45 municipalities in the region, regenerating 23 degraded sites. Inputs and outputs are redefined from an eco-effective approach. The network is conceived considering the interactions with the SES, simulated through a system dynamics model. An optimisation model is developed, proposing network configurations that maximise profit and net GHG savings. The performance of the waste network is evaluated in terms of economic, environmental and social dimensions, and resilience is checked with the Ecosystem Network Analysis model.

The remainder of this chapter is organised as follows: a background section related with the research is presented. The development of the supply network is described, starting by the case explanation and going through the design steps. Results and discussion follow, with an evaluation of the performance of the solutions achieved. Last, a conclusion is presented with final remarks and research limitations.

4.1 BACKGROUND

First, linked with the research purpose, principles of land regeneration - also known as Sustainable Brownfield Regeneration - are introduced. Next, waste recovery options used in this research are briefly explained, followed by a section about Integrated Municipal Solid Waste Management. The last subsection brings researches on dynamics of waste management systems and optimisation.

4.1.1 REGENERATION OF DEGRADED SITES BY WASTE DISPOSAL

In this subsection, four regeneration strategies are reviewed: reforestation, enhanced landfill mining, transformation into (i) solar farms, or (ii) recreational parks. **Reforestation** "is the natural or intentional restocking of existing forests and woodlands (forestation) that have been depleted, usually through deforestation." (Wikipedia contributors, 2018f). It is known that tropical forests mitigate global warming not only through GHG capturing from the atmosphere, but also through cloud formation, which reflects sunlight (CANADELL; RAUPACH, 2008). In this research, reforestation is defined as the planting of native tree species on the degraded site, reestablishing local forests that require only minor maintenance.

Landfill Mining is defined as the recovery and valorisation of landfill waste through Waste-to-materials or Waste-to-energy transformations (DANTHUREBANDARA et al., 2015; PASSEL et al., 2013). **Enhanced Landfill Mining** (ELM) aims to optimise energy and material recovery with negligible residual waste volumes, achieving environmental benefits through more environmentally friendly processes (DANTHUREBANDARA et al., 2015). ELM has recently grown in momentum in Europe due to land availability constraints and the long-term damage related with GHG emissions, soil and water contamination, caused by landfills (DANTHUREBANDARA et al., 2015; PASSEL et al., 2013).

Converting old dump sites or landfills into **Solar farms** has been increasingly explored as an alternative to recover brownfields. These areas are not recommended for agricultural or other productive purposes, while showing a great potential for transportation and installation of photovoltaic solar panels, since these terrains feature road infrastructure and electricity connections (SZABÓ et al., 2017). Finally, transforming old dump sites into **Recreational Parks** is interesting for urban areas with scarcity of urban space. Previously located away from city premises, many landfills have become part of the city landscape due to urban expansion (SIMIS et al., 2016). Transforming these areas into public parks brings benefits like enhanced quality of life for the neighbours (SIMIS et al., 2016), along with GHG capturing.

It is not only necessary to regenerate the degraded sites, but also to redesign the current waste management system to halt the degradation of other sites, taking advantage of recovery processes that add value to waste. Waste recovery options used in this research are reviewed in the following subsection.

4.1.2 WASTE RECOVERY OPTIONS

Usual material transformations are represented in Figure 29, from raw material extraction: waste is generated after consumption or use of manufactured products. Every transformation emits GHG, while some of them can also avoid emissions, like Mechanical Biological Treatment and Anaerobic Digestion. In this subsection, five waste destinations adopted in this research are overviewed, considering also their development in the regional, Brazilian context: sorting of recyclables, aerobic composting, anaerobic digestion, gasification and sanitary landfill.

Recovering waste starts with its collection, which can be performed in three different ways: (i) **all-mixed collection stream**, where households dispose all the waste in a single bin; (ii) **single-stream (SS) collection**, where recyclable waste is segregated from organic and rejected waste, and (iii) **multi- or double-stream collection**, where households are required to separate recyclables in two or more bins (LAKHAN, 2015). SS collection appears to be the most effective choice, since communities find it easier to adhere than multi-stream (FITZGERALD et al., 2012).

Recyclables Sorting is defined by the activities of (i) collecting the recyclable waste from households that perform SS disposal, (ii) screening and pre-treatment and (iii) packing in bundles, which are sold and transported to recycling facilities for further processing (XAVIER, 2015). In low- and middle-income countries, this activity is often performed by cooperatives of waste pickers from the informal sector (KING; GUTBERLET, 2013). The remaining fraction of sorting normally goes to landfill (CONKE; NASCIMENTO, 2018). Normally, recyclables are clustered in four major groups: paper, plastic, metal and glass (ANNEPU, 2012; CLIFT; DRUCKMAN, 2016; CANNON, 2015; THI, 2012). Categories with bigger volumes can also be subdivided in, e.g., types of plastic, paper. Recyclable types with low volume are normally clustered in an “others" group.

Aerobic (Windrow) Composting aims to treat organic, biodegradable waste. It is performed in outdoor facilities, where gaseous emissions are released to the atmosphere. Waste is disposed in trapezoidal windrows around the floor, and periodically turned around to homogenise the compost (BOLDRIN et al., 2009). The whole composting process, if performed with the addiction of enzymes and proper turning, takes around 40 days (PIRES, 2011). **Anaerobic Digestion** also treats organic waste, and can be performed in an engineered reactor, where, in the absence of oxygen, bacteria decomposes the particulate matter, producing biogas and digestate. The biogas can be used to generate electricity and heat, while the digestate can be used as a biofertilizer for farming (DISTEFANO; BELENKY, 2009; EVANGELISTI et al., 2014; SALEMDEEB et al., 2017). From a waste-to-energy perspective, it is considered as the best option for food and yard waste (KUMAR; SAMADDER, 2017).

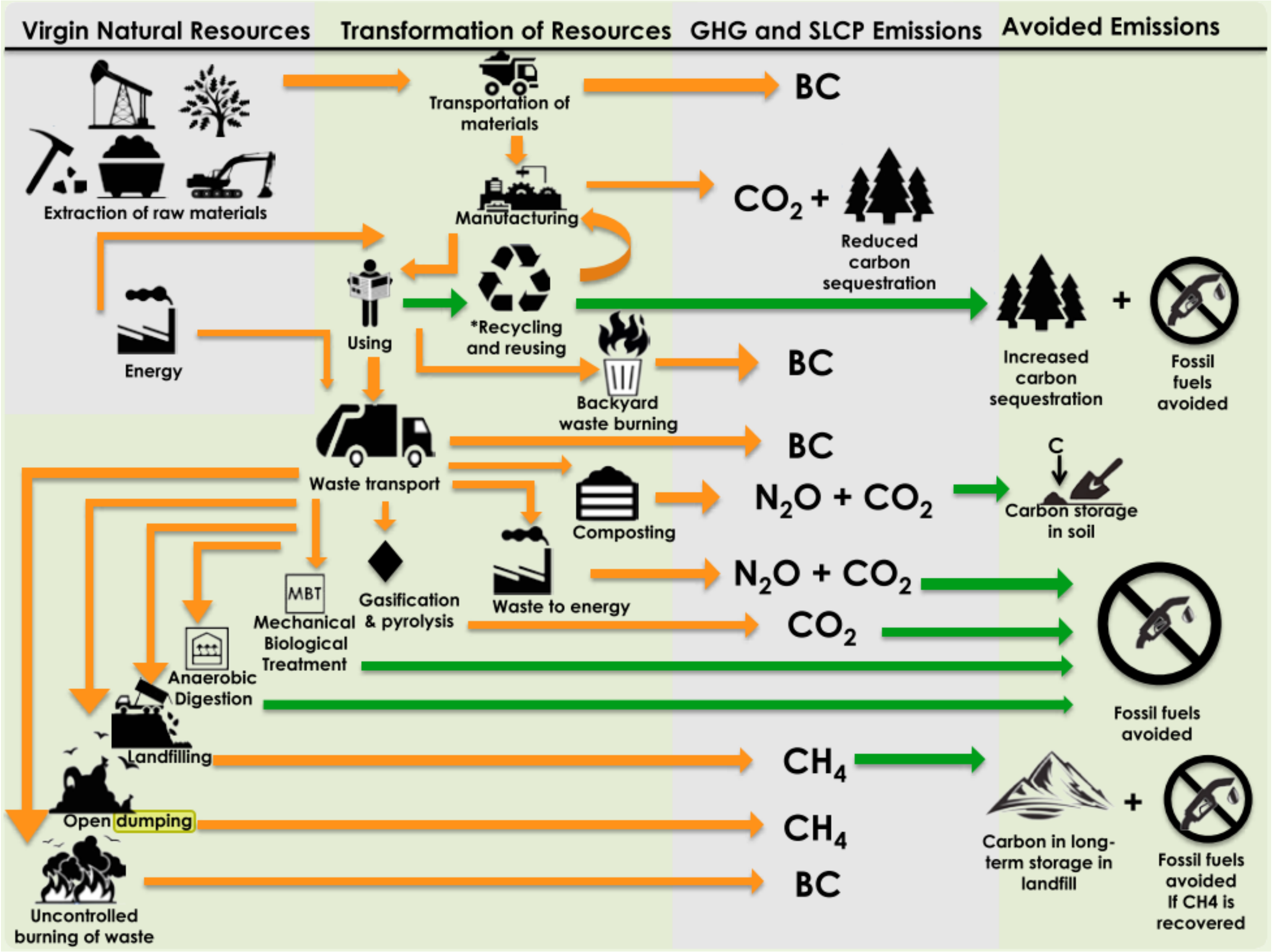


Figure 29: Waste destinations and their consequences. Source: Cannon (2015).

Gasification is the conversion of waste into syngas under controlled conditions, with temperatures that can reach 1,600^{o}C. The syngas can be used to produce electricity through combustion (KUMAR; SAMADDER, 2017). Gasification is considered more environmental friendly than incineration due to its higher energetic efficiency with less GHG emissions and reduced chance of water and soil contamination (KUMAR; SAMADDER, 2017). However, it faces criticism from environmentalists and NGOs, that defend that burning waste may perpetuate waste disposal: “If you build incinerators it creates a market for the next 20 years for single-use plastics, which is the very thing we need to be reducing right now." (HARRABIN, 2018).

Sanitary Landfilling is the disposal of waste in Sanitary Landfills: facilities adequately located and prepared to protect the underground from leaches, and may feature a gas collection system (MANFREDI et al., 2009). Sanitary landfills are normally designed for a 20-year lifespan, considering current waste generation volumes (RIBEIRO et al., 2008). However, due to the increase of waste generated, this lifespan can be dramatically reduced, causing the sanitary landfill to overload, making it improper for waste disposal.

The advantages and disadvantages of each process are listed in Table 7. With many options available to recover waste, the question becomes how to integrate them into an Integrated Solid Waste Management, reviewed in the following subsection.

4.1.3 INTEGRATED MUNICIPAL SOLID WASTE MANAGEMENT

Integrated Municipal Solid Waste Management (IMSWM) is defined as the combination of “appropriate treatment methods such as recycling, anaerobic digestion, incineration, landfilling, etc., required for proper, balanced MSW management”, resulting in the recovery of useful materials and production of energy (MENIKPURA et al., 2013). The potential of an IMSWM for saving net GHG can be determined using the framework illustrated in Figure 30. The box on the right outlines the GHG emissions from transportation, processing and final disposal of waste. The box on the left represents the GHG avoided from replacing virgin products by their recovered counterparts, and from diverting organic waste from landfills. In the centre of the diagram, waste processing options are listed, with the corresponding waste type processed; every process causes impacts and benefits. System’s net GHG savings is defined in the bottom of the diagram box, as the subtraction of the emitted GHG from the avoided/saved GHG.

Treatment	**Advantages**	**Disadvantages**
Recyclables Sorting	• Generates employment opportunities and income for urban-low income people; • Very low environmental impact.	• Informal sector lacks structuring, organisation and support from policies and the government.
Aerobic Composting	• Simple technology required.	• Use of compost in farming is still under debate, due to uncertain composition that may even contain heavy metals.
Anaerobic Composting	• Biomass pre-treatment not required; • Simple, reliable generation of biogas.	• Requires technical knowledge, and in some cases, large investments; • Use of digestate for farming is still under debate.
Gaseification	• High energy recovery efficiency; • Syngas can be used for the production of valuable chemicals.	• Difficult acceptance from local communities; • Still in the early stages of implementation for processing large volumes of waste.
Sanitary Landfilling	• Carbon storage in the long term.	• All the energetic value of the waste is lost; • May result in leaches that threaten underground ecosystems; • Limited lifespan due to capacity constraints: must be shutdown when full, which normally is not respected; • Considerable land requirement.

Table 7: Advantages and Disadvantages per Waste Recovery Option.

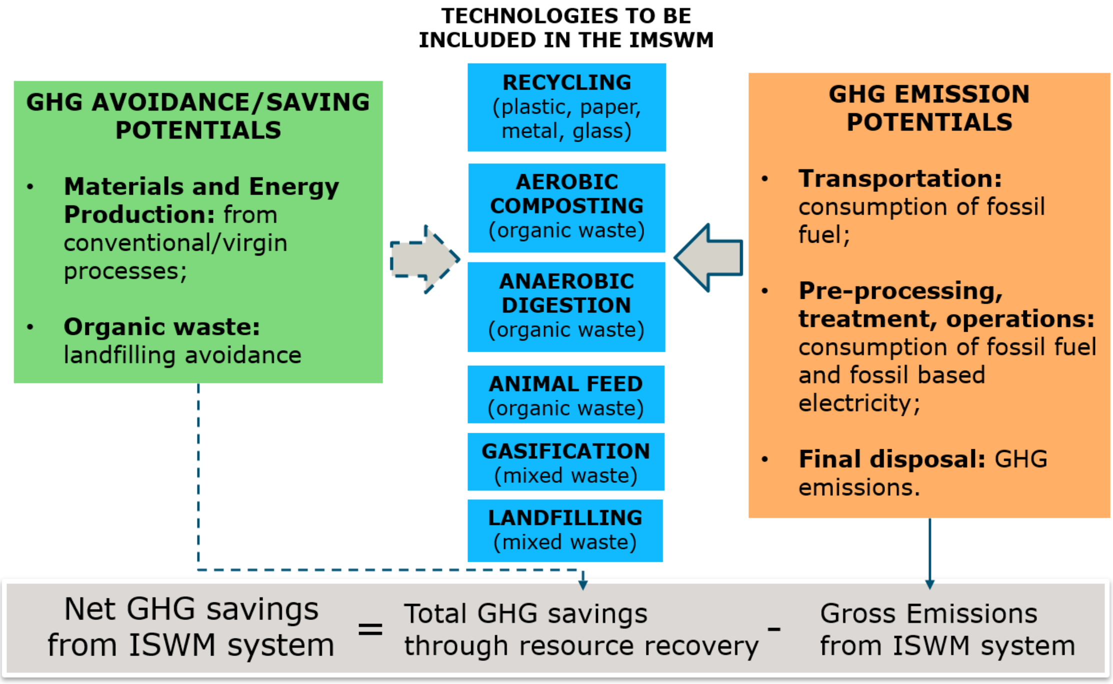


Figure 30: Integrated Municipal Solid Waste Management Performance Framework. Source: based in Menikpura et al. (2013).

Concerning decision-making during the design of IMSWMs, two research trends have been explored: optimal location of waste treatment plants and optimal choice of recovery processes/technologies, through mixed-integer linear programming (MILP), which may lead to complicated mathematical models. ThiKimOanh et al. (2015) developed a single-objective (minimise costs), MILP model, indicating the technology mix, total costs, plant locations and utilisation, output production and land use, for three scenarios. Results showed the dramatic reduction in landfilled waste while generating revenues. Sensitivity analysis revealed that the price of outputs have a major effect on the selection of the waste recovery process.

In the context of industrial networks, Vadenbo et al. (2014) performed a systemic evaluation of waste recovery, defining each waste facility as a node which either process, mix or split mass streams. Using MILP optimisation, they evaluated the economic and environmental performances of a glass recycling system. (TAN et al., 2014) designed an optimal IMSWM system, also through MILP,investigating cost and GHG emissions in the region of Iskandar, Malaysia. Four scenarios were developed: business-as-usual, waste-to-energy, waste-to-recycling, and one called MIXTECH, which stands for a mix between the previous two strategies, outperforming both in environmental performance.

Bing et al. (2015) explored the influence of emission trading schemes on the design of reverse household plastic supply chains involving Europe and China. A MILP formulation was used to reallocate intermediate processors, minimising costs (including carbon trading costs). Multiple scenarios were analysed, with different percentages of waste reprocessed in Europe, China, or both. Results showed the potential China features for processing waste, taking advantage of empty containers returning from Europe to China to transport the waste. Specifically in this case, it is interesting to note how governance dynamics interfere in the performance of waste management systems, as China recently banned waste imports from Europe to decrease pollution within their territory (LEE, 2018).

In the research stream of system dynamics for waste management, Ghisolfi et al. (2017) modelled the impact of the formalisation of waste pickers in the closed-loop supply chain of desktops and laptops. They compared implementation levels of formalisation policies, analysing effects like the increased amount of recyclable waste available for processing, which also implies on increasing the demand to absorb this extra quantity. Dyson e Chang (2005) investigated waste generation forecasting for the city of San Antonio, Texas. Five simulation models were developed based in multiple driving factors. After comparing the results of the SD models with the historical series and statistical regression model, they concluded that the model on total income per service centre showed more accurate results.

Sukholthaman e Sharp (2016) investigated the impact of source separation in waste collection and transportation, monthly expenses, landfill life, and service satisfaction, for a waste management system in Bangkok. Six scenarios were developed, varying households disposal behaviour and the rate of source separation. They analysed the relation between waste separation attitudes with knowledge and incentives, concluding that the two latter influence the former positively, recommending strategies for the MSWM system. Guo et al. (2016) investigated the promotion of appropriate waste disposal behaviour in the low-income urban area of Baltimore, Maryland. Twelve interventions were tested, focused on variables that influence the waste disposal choice: social norms, financial incentives, contextual factors, knowledge and physical cleaning. Effects of each intervention were analysed in aspects like population of rats and accumulation of litter. Interventions focused on social norms and financial incentives showed the best results.

In the following section, the design & development of the waste management network is presented. The Regenerative Supply Network Design procedure described in chapter 3 was followed. Section 4.3 describes how these steps were performed for the case study of designing an IMSWM to regenerate degraded sites in the region of Norte Pioneiro, corresponding to the Demonstration activity in the Design Science Research Methodology (DSRM). Section 4.4, Results and Discussion, corresponds to the activity of Evaluation from DSRM.

Municipality Population range	MSW *per capita* (kg/day)	Waste types (per kg of MSW)		
		rW	*oW*	*wW*
Under 15 thousand	0.63	0.27	0.6	0.13
Over 15 and under 50 thousand	0.73	0.27	0.6	0.13
Over 50 and under 100 thousand	0.73	0.34	0.49	0.17

Table 8: Waste generated *per capita* and fractions by waste type.
Source: Envex e Engebio (2018c).

4.2 DESIGNING THE WASTE MANAGEMENT NETWORK

In this section, the activities performed for the design of the regenerative waste management network are described. The RSND procedure described in chapter three is followed, and the four stages were completed. First, the analysis of the surrounding SES is presented, then the inputs and outputs redesign. Network conceptualisation follows, consisting of the modelling of interactions between the SES, the waste network flow diagram and the regeneration strategies algorithm for degraded sites. Finally, performance optimisation of the network is detailed, with a description of the mathematical model including sets, variables, optimisation functions and constraints. Last, information about the computer model configuration and model runs is provided.

4.2.1 SES DESCRIPTION AND PURPOSE IDENTIFICATION

The state of Paraná is located in Southern Brazil, with an area of almost 200 hundred thousand square meters (IPARDES, 2018). To improve the waste management, in the waste management state plan *PERS* (Engebio, 2013), the state was divided in twenty “micro regions", with the region of Norte Pioneiro (“Pioneer North”, in a free translation), located in the northeast of the state, consisting of micro regions R6 - Cornelio Procópio -, and R7, Jacarezinho, as illustrated in Figure 31. Norte Pioneiro (NP) is divided in 45 municipalities – 21 in R6 and 24 in R7. In 2016, the population of NP surpassed 552,218 inhabitants (IBGE, 2010).

Waste generation data used is based on Envex e Engebio (2018c), and its summarised in Table 8. Waste generated is categorised in three types: recyclable (rW) – consisting of glass, plastic, paper, metal and others -, organic (oW) – which is all the degradable waste -, and the remaining waste fraction, which normally cannot be recovered, referred as “wasted” Waste (wW). Waste generated per *capita* increases with the municipality’s population size, as well as the fraction of recyclable and wasted waste. The largest fraction among the three types is of organic waste, which decreases as population increases.

Figure 31: The mesoregion of Norte Pioneiro, Paraná, divided in Regions 6 (in gold colour) and Region 7 (yellow).
Source: IPARDES (2010), Wikipedia contributors (2018g).

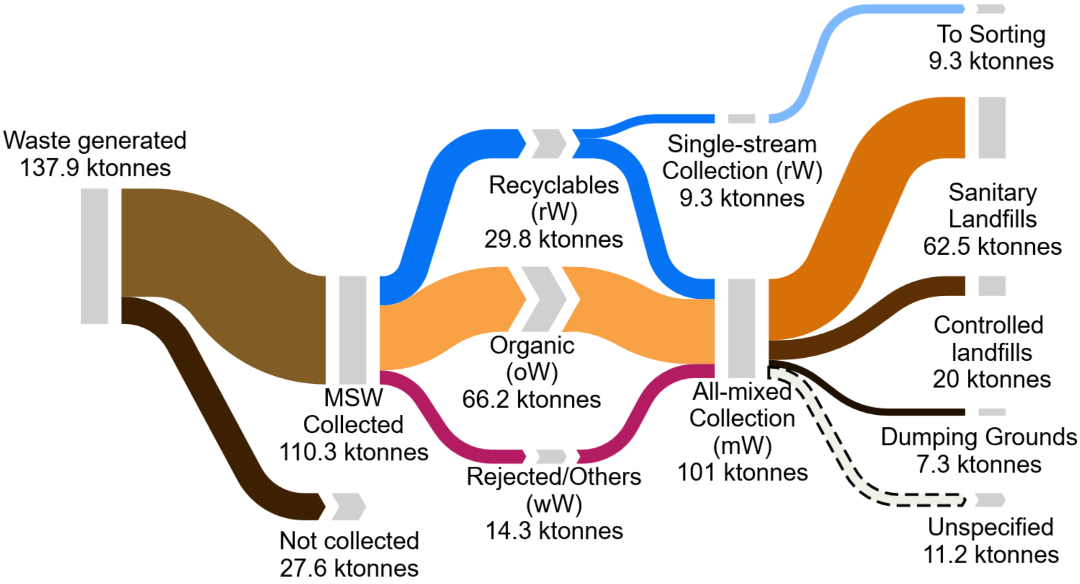


Figure 32: Sankey diagram of 2016 MSW destination in Norte Pioneiro, Paraná. Created with www.sankeyflowshow.com.

A Sankey Diagram of the current MSW generation, collection and disposal in the Norte Pioneiro is presented in Figure 32. The quantity of Waste generated is estimated from the product between the population size (see Table C1 in Appendix C) and the waste generated per *capita*. Waste data is based in Brasil (2016); around 80% of the total waste generated is collected by municipalities, which is split in the three waste types: recyclables (29.8 ktonnes), organic (66.2 ktonnes) and wasted waste (14.3 ktonnes). From the total recyclables collected, only a fraction is done through SS, and sorted (9.3 ktonnes): the remaining fraction is mixed with the organic and wasted waste, which is mostly landfilled.

Controlled landfills, Dumping Grounds and Sanitary Landfills with expired operation licenses are categorised as inadequate waste disposal (Envex; Engebio, 2018b). In total, at least 81% of the waste is landfilled: "unspecified" accounts for the difference between the reported quantities of waste collected and landfilled in the Brasil (2016) report. It is possible to observe that the STS responsible for managing the waste is a major responsible for land degradation to the SES it is nestled, consequence of massive landfilling, the least desirable waste disposal option, environmentally speaking. Therefore, *land use* arises as one of the main problems related with the current configuration of the waste management system.

An extensive list of current and disabled landfills in the state of Paraná can be found in Envex e Engebio (2018b). Table C2 in Appendix C is an extract of that report, and lists 23 degraded sites by waste disposal in the region of Norte Pioneiro, in a total of 127 hectares. Most of the sites were dumping grounds; some of them are still operational. The waste stock for each site was estimated from GPS observation with Google maps and waste disposal data in Brasil (2016), from 2006 until 2015.

A verification on land use of the Norte Pioneiro region is also performed: Figure 33 contains a map of the major land use activities. The region has been mostly explored for grazing, intensive agriculture and mixed use. From the original forest, only a few areas remain, and reforestation areas are scarce. An unbalanced land use is evident, putting in danger the ecosystem's resilience (KIM et al., 2017). Finally, after the description of the environmental situation of the SES, a twofold purpose is defined: i) to divert waste flows from landfills and ii) to regenerate degraded areas from inadequate waste disposal. To achieve this purpose, next step is to redefine the network outputs.

4.2.2 REDESIGN OUTPUTS

First, organic waste recovery options were ranked from an eco-effective perspective. A search over the literature revealed multiple recovery hierarchies, but neither of which properly

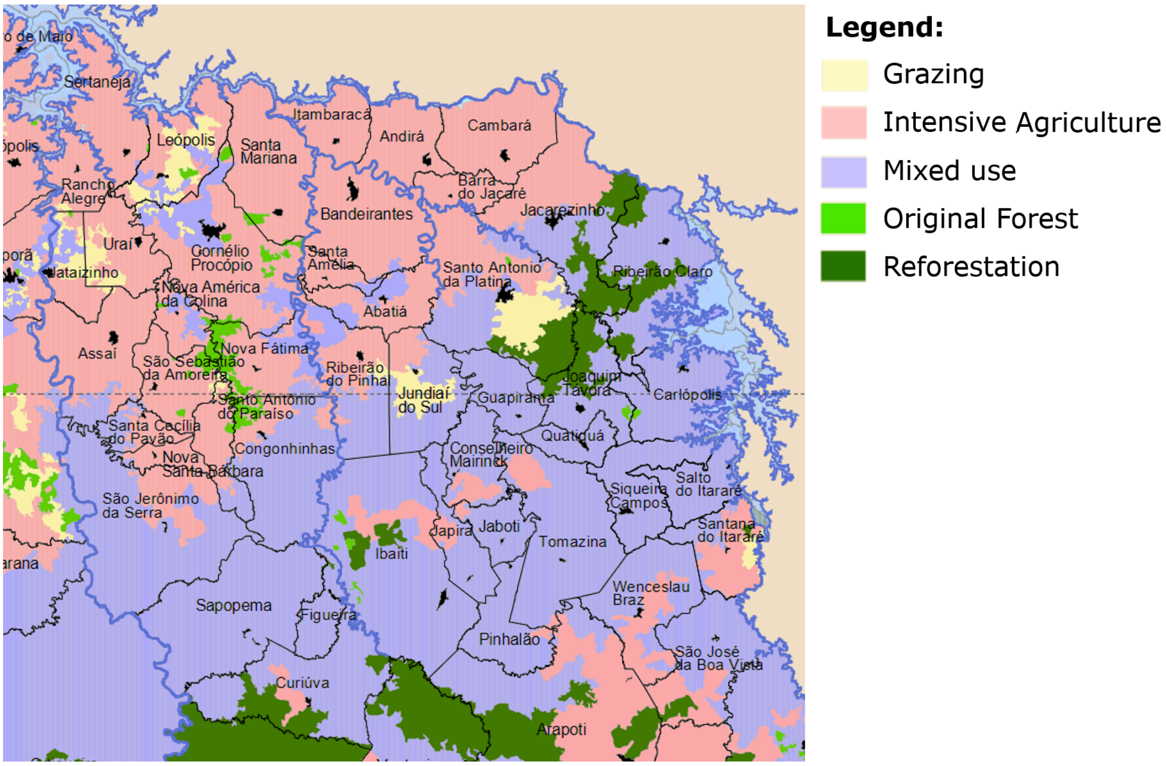


Figure 33: Land use situation in Norte Pioneiro. Source: ITCG (2008).

fitted the context of this research, nor provided the required level of detail. Based in 3R – Reduce, Reuse and Recycle, a specific waste hierarchy pyramid was created, and is presented in Figure 34. The pyramid's base is facing up, indicating that most of the waste should be reduced, and the smallest quantity should be landfilled.

The least preferred strategy is waste landfilling with methane burning, ranked worst in environmental impacts as no value is recovered from waste. Second worst is sanitary landfilling without methane capture. One level higher is the option of landfilling with methane flaring and, finally, the least bad option is to make use of sanitary landfills with capture and use of the CH_4 produced. Following eco-effectiveness principles, no waste should be landfilled, but reintroduced to a production chain or upcycled.

Next up in the hierarchy are the waste recycling options, starting with Waste-to-Energy (WTE), i.e., converting waste into thermal or chemical energy. Then, composting is a better option; anaerobic digestion is preferred for capturing also the biogas from the organic degradation process. Finally, from the strategy of Reuse, organic waste could become animal feed or be given to the hunger. Different processes can be used for WTE, aerobic composting and anaerobic digestion. In WTE, Incineration is the least preferred, then Refused-derived fuel, Plasma, Pyrolysis and, the most preferred, Gasification. For Aerobic Composting, Windrow Composting is preferred rather than Vermi-composting. For Anaerobic Composting, large scale

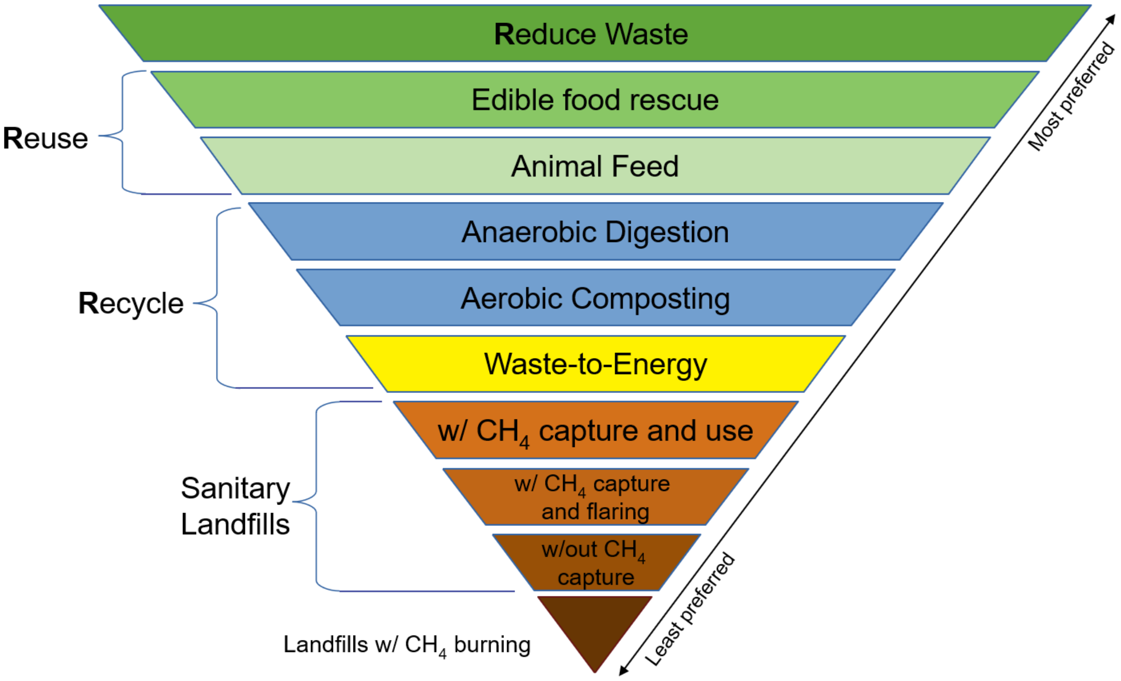


Figure 34: Organic Waste Recovery Hierarchy.
Source: based in Annepu (2012), EPA (2015), Wikipedia contributors (2018d).

biogas production is preferred rather than small scale.

The waste recovery processes selected are listed in Table 9, with respective inputs, outputs and by-products. Inputs and outputs are defined in terms of the waste types processed. Anaerobic Digestion plants and Aerobic Composting Centres that process the mixed waste sort the recyclable and rejected waste from the organic, considering these waste types as other outputs of the process.

Gasification can process rejected, wasted and mined landfill waste to produce electricity. The only by-product from gasification are the combustion ashes. Sanitary Landfills are indicated only for the residual waste generated by the system, ashes from gasification, which, when landfilled, have a low potential to produce Methane gas (MANFREDI et al., 2009), comparing with raw, organic waste landfill. In this research, it is considered that ashes generate five times less the impact generated by raw, organic waste landfill. Ashes can also be diverted from landfilling, for cement production Wang et al. (2010).

The processes were chosen due to contextual factors, like previous data from successful implementations, technology availability and familiarity. Waste reuse to animal and human feed were not considered due to the moderately advanced degradation stage of household waste. Waste reduction is considered as an outcome of policy strategies derived from PERS (Envex; Engebio, 2018a). For recyclables, only the sorting process is considered within the system

Recovery option	Inputs (waste types)	Outputs	By-products
Sorting	rW (SSC)	Recyclables	$rejW^1$
Anaerobic Digestion	mW (AMC)	Electricity	$rejW^2, wW^3$
		Digestate	
		Recyclables	
Aerobic Composting	mW (AMC)	Compost	$rejW^2, wW^3$
		Recyclables	
Gasification	$rejW^2$, wW^3, dsW^4	Electricity	$resW^5$ (Ashes)
		Recyclables	
Sanitary Landfill	$resW^5$	-	-

[1] Rejected Recyclables in sorting; [2] Rejected recyclables and organic.
[3] wasted waste from sorting; [4] mined waste from degraded sites.
[5] residual waste.

Table 9: Waste recovery options with respective inputs, outputs and by-products.

scope. In the following section, the conceptual model development of the network is described.

4.2.3 NETWORK CONCEPTUALISATION

A closed-loop cycle of food and products production, distribution, consumption, disposal, collection, transportation, processing, commercialisation and recycling is represented in Figure 35. The orange, dashed-dot polygon limits the research scope to the phases of consumption, disposal, collection, transportation and processing. Two models where developed: a system dynamics model (FORRESTER, 1994), delimited by the grey-shaded square, simulating consumption and disposal behaviour of households, and collection rates in municipalities. The outputs of the SD model - the yearly waste collected for each municipality - are inputs for the IMSWM network, delimited by the blue-dotted square.

The waste management network consists of the transportation and processing of mixed and source-separated waste. The rejected waste from processing is sent to gasification, along with waste mined from degraded sites – a sub-network specifically dedicated for regeneration, represented by the dash-double-dot square. The residual waste (ashes) is disposed in sanitary landfills, or used. Organic outputs can be used in farming to improve soil quality; recyclables are commercialised, energy is produced, and ashes can be used as raw material for cement production. After being mined, each degraded site is regenerated.

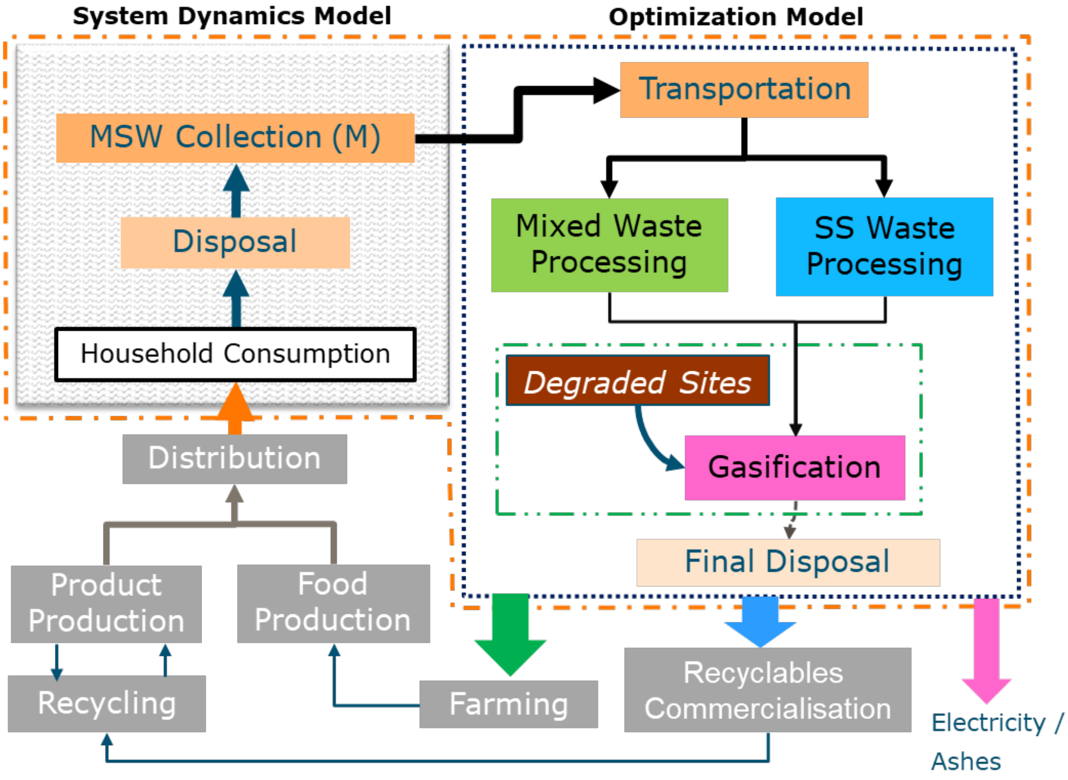


Figure 35: System Flow Diagram. Based on Conke e Nascimento (2018).

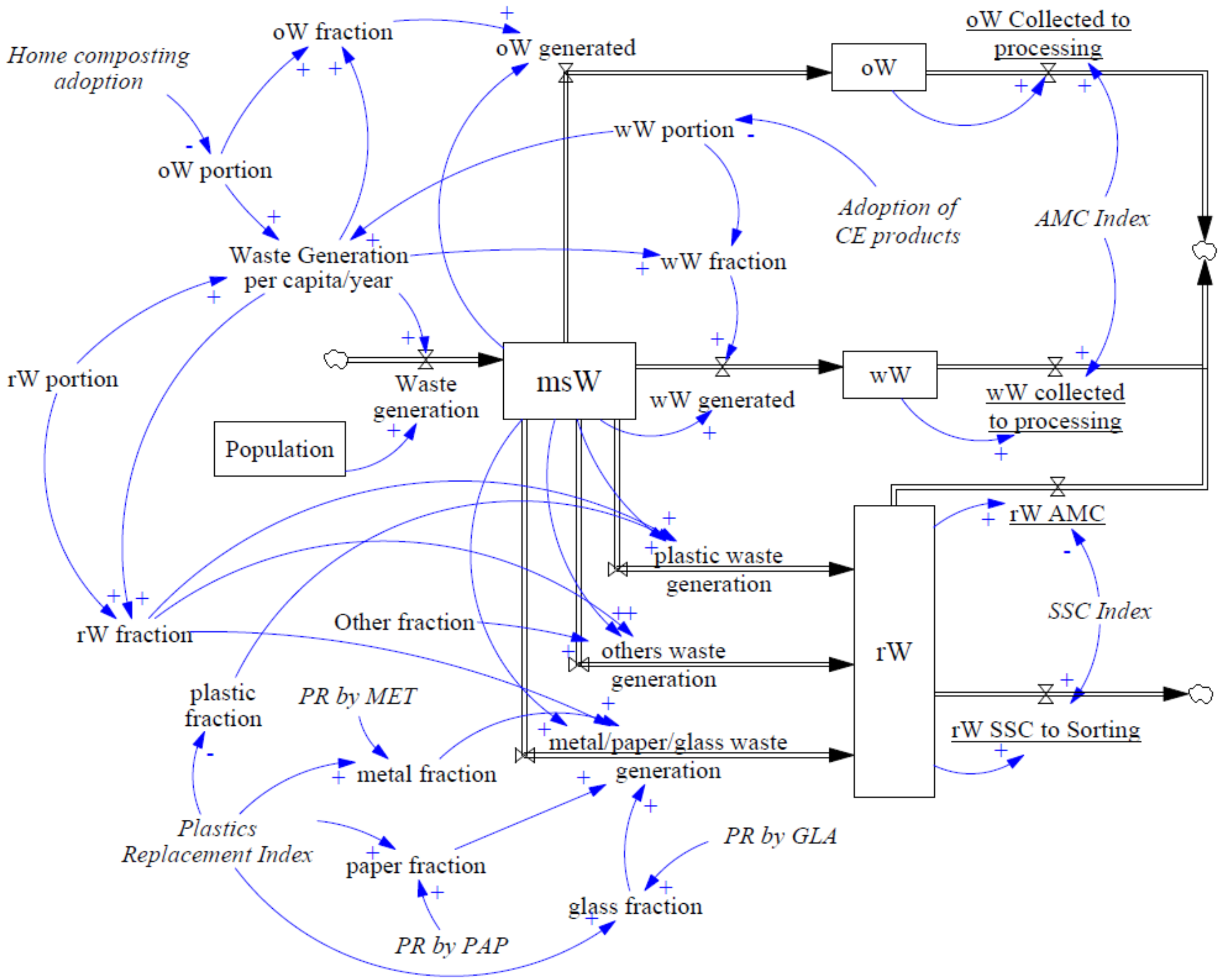


Figure 36: Stock and Flows diagram of the waste generation dynamics.

4.2.3.1 CONSUMPTION, DISPOSAL AND COLLECTION

The influence of waste generation (a consequence of consumption), disposal and collection dynamics in the network configuration and performance is investigated through a SD Stock and Flows simulation model, representing the SES interacting with the waste management network. The model was developed using Vensim PLE x32, and is presented in Figure 36. Objectives defined in the waste management state program in Envex e Engebio (2018a) and considered in this research are: reduce waste generation, increase waste collection and increase waste fraction collected through SS. The diagram is explained through the variables and formulas described in the following paragraphs.

Daily Waste Generation Per *Capita*, $WGPC$, is calculated as the weighted average of waste generation *per capita* for the Region of Norte Pioneiro, as defined by Equation 2. Pop_{un15} is the sum of the population of municipalities with less then 15 thousand inhabitants, and $Pop_{ov15un50}$ is the sum of the population of municipalities with over 15 and under 50 thousand. Municipality population data is in Table C1 in Appendix C. All municipalities in the region have less than 50 thousand inhabitants. Values in the Equation come from 8.

$$WGPC = \frac{Pop_{un15} \times 0.63 \ + \ Pop_{ov15un50} \times 0.73}{Pop_{un15} + \ Pop_{ov15un50}} \tag{2}$$

Fractions for each waste type – organic, recyclable and wasted – were determined by multiplying the fractions from Table 8 by the weighted average. Results found for $WGPC$ and the respective portions of oW, rW and wW are listed in Table 10.

Waste Type	Portion (kg per capita/day)
$WGPC$	0.690
oW	0.414
rW	0.186
wW	0.090

Table 10: Average waste portions considered for the region of Norte Pioneiro.

Waste generation scenarios were developed based in four population size scenario forecasts from Envex e Engebio (2018c) for the region of Norte Pioneiro, according to the economic development: Stagnation (ST), Slow Recovery (SR), Growth Resumption (GR) and Acceleration (AC) - denoted by s. Population size is projected for a 21-year period, from 2018 until 2038. Equation 3 defines the total municipal solid waste generated, MSW, for for each scenario s and year t, in tonnes.

$$MSW_{s,t} = (0.414 - HCA_t + 0.186 + 0.090 - AceP_t) \times Pop_{s,t} \times \frac{365}{1000}, \ \forall s,t \tag{3}$$

Recyclable Type	Fraction (kg/kg)
Plastic	0.3710
Paper	0.3720
Metal	0.1140
Glass	0.0194
Other	0.1236

Table 11: Fractions by Recyclable Waste Type. Source: Xavier (2013).

Values inside the parenthesis correspond to the portions of oW, rW and wW, respectively. Two waste reduction strategies are considered: *HCA*, the *Home Composting Adoption Rate* - when home composting is adopted by households, decreasing the generation of organic waste -, and *AceP*, the rate of *Adoption of CE products* - increasing the adoption of circular products decreases the generation of "wasted" waste. *Pop* is the population size forecast for region NP, for scenario s at time t. Last term of the Equation transforms kilograms per day in tonnes per year.

From the total *MSW* generated, fractions for each recyclable type - glass, paper, plastic, metal and others - are determined by Equations 4 to 8, for each scenario s and period t. Fractions per recyclable type are listed in Table 11, based in Xavier (2013). A strategy to decrease plastic waste, replacing it by other recyclable types (glass, paper or metal) was also modelled, and is represented by the variable PRI_t - Plastics Replacement Index, for each period t. $plaW$ is the quantity of plastic waste generated, rwF_t is the recyclables fraction within the MSW, which also varies with time as the portions of oW and rW change.

$$plaW_{s,t} = MSW_{s,t} \times [0.371 \times (1 - PRI_t)] \times rwF_t, \ \forall s,t \tag{4}$$

Equations 5, 6 and 7 defines the paper, metal and glass waste quantities, $papW$, $metW$ and $glaW$, for each scenario s and period t, respectively. $papW$, $metW$ and $glaW$ are in opposition with $plaW$, increasing with *PRI* and the plastic waste fractions replaced by paper, metal or glass - *prPAP*, *prMET* or *prGLA* - increase. The quantity of other recyclables within the recyclable waste, $othW$, is determined through Equation 8.

$$papW_{s,t} = MSW_{s,t} \times [0.372 + (0.371 \times PRI_t \times prPAP_t)] \times rwF_t, \qquad \forall s,t \tag{5}$$

$$metW_{s,t} = MSW_{s,t} \times [0.114 + (0.371 \times PRI_t \times prMET_t)] \times rwF_t, \qquad \forall s,t \tag{6}$$

$$glaW_{s,t} = MSW_{s,t} \times [0.0194 + (0.371 \times PRI_t \times prGLA_t)] \times rwF_t, \qquad \forall s,t \tag{7}$$

$$othW_{s,t} = MSW_{s,t} \times 0.1236 \times rwF_t, \qquad \forall s,t \tag{8}$$

The recyclable waste, rW, is the sum of all recyclable waste types generated, for each scenario s at time t, defined in Equation 9.

$$rW_{s,t} = plaW_{s,t} + papW_{s,t} + metW_{s,t} + glaW_{s,t} + othW_{s,t}, \ \forall s,t \tag{9}$$

Finally, the collection rates were also determined according to the targets defined in PERS, and adjusted using current data from Brasil (2016) for the region of NP. Equations 10 to 12 define waste flows oW^{AMC}, organic waste collected through AMC, wW^{AMC}, wasted waste collected through AMC, rW^{AMC}, recyclables collected through AMC, and rW^{SSC}, recyclables collected through Single-Stream. $AMCI$ is the All-mixed Collection Index at time t, i.e., the fraction of the waste generated, collected all-mixed, whereas $SSCI$ is the fraction of recyclable waste generated that is collected through single-stream.

$$oW^{AMC}_{s,t} = MSW_{s,t} \times owF_t \times AMCI_t, \qquad \forall s,t \tag{10}$$

$$wW^{AMC}_{s,t} = MSW_{s,t} \times wwF_t \times AMCI_t, \qquad \forall s,t \tag{11}$$

$$rW^{AMC}_{s,t} = rW_{s,t} \times (1 - SSCI_t), \qquad \forall s,t \tag{12}$$

$$rW^{SSC}_{s,t} = rW_{s,t} \times SSCI_t, \qquad \forall s,t \tag{13}$$

The evolution of each the implementation of each strategy is presented in Table 12, and they follow four period ranges defined in PERS: immediate term (from 2018 until 2021), short-term (2021 until 2024), mid-term (2024 until 2032) and long-term, from 2032 until 2038. The percentage of organic waste being composted starts from zero and increases until four per cent at 2032, remaining in this level until 2038. The generation of waste waste reduces up until two per cent from 2032 onwards, due to the adoption of circular products. Plastic products are replaced by the other three major recyclables up to twenty per cent. Collection rates also increase, and by 2032, every municipality features SS waste collection.

For each recyclable type, replacement percentages are also defined in Table 12. It is assumed that plastic is mostly replaced by glass, specially for packaging. Such balance changes over time, and the distribution becomes more uniform from 2032 onwards, where fifty percent of the plastic is replaced by glass, and the other fifty percent is equally replaced by paper and metal, 25% for each. Source Separation is assumed as performed by 100% of the population. Equation 14 defines the municipal solid waste collected, $msWC$, for each scenario s and period t, as the sum of the organic, wasted, mixed and separated recyclables.

$$msWC_{s,t} = oW^{AMC}_{s,t} + wW^{AMC}_{s,t} + rW^{AMC}_{s,t} + rW^{SSC}_{s,t}, \forall s,t \tag{14}$$

Figure 37 illustrates the evolution of the quantities of waste collected, $msWC$, for all

	Horizons			
	2018-2021	2021-2024	2024-2032	2032-2038
Strategy				
Home Composting (*HCA*)	0.0%	2.0%	2.6%	4.0%
CE products (*AceP*)	0.0%	0.0%	0.7%	2.0%
Plastics Replacement (*PRI*)	0%	5%	10%	20%
AMC Collection (*AMCI*)	65%	65%	80%	100%
SSC Collection (*SSCI*)	23%	30%	60%	100%
Recyclable Type				
Paper (*prPAP*)	0%	20%	20%	25%
Metal (*prMET*)	0%	20%	20%	25%
Glass (*prGLA*)	0%	60%	60%	50%

Table 12: Progression of Strategies and Plastics Replacement through time.

four scenarios, from 2018 until 2038. The scenario Slow Recovery (SR) is considered the base case scenario, since it is the most probable. Scenario Stagnation (ST) shows the lowest quantities of waste generated, and Grow Resumption (GR) shows more waste generated than SR. The three scenarios show proximity among each other as GR appears to be symmetrically in opposition to ST. Scenario Acceleration shows the largest amount of waste collected, with a considerable difference from the other three. There are two spikes in the curves in years 2024 and 2032, due to the increase in the collection rates, which are later attenuated by the gradual implementation of the waste reduction strategies.

Figure 38 presents the quantities of recyclable waste generated through the 21-year period for scenario Acceleration - this scenario was chosen for better illustration since its oscillations show more amplitude. Again, around years 2024 and 2032, oscillations can be noticed in the curves; plastic volumes decrease significantly, increasing again following the increase in the overall waste generation. Paper, metal and glass wastes volumes increase abruptly, but oscillates downwards as well.

The SD model outputs quantities of recyclables, organic, and wasted waste collected via AMC, the recyclable waste collected via SSC, and the fractions of recyclable types for each of the four scenarios, for each year in the 21-year period. These quantities will be processed by the waste management network, which conceptual model is described next.

4.2.3.2 THE IMSWM NETWORK

First, quantities of waste collected through AMC and SSC, $rW_{m,t}$ and $mW_{m,t}$ are determined for each municipality m, at each year t. The index s used to symbolise the scenarios is dropped from this point onwards, as the focus turn to the elements in the network - the same

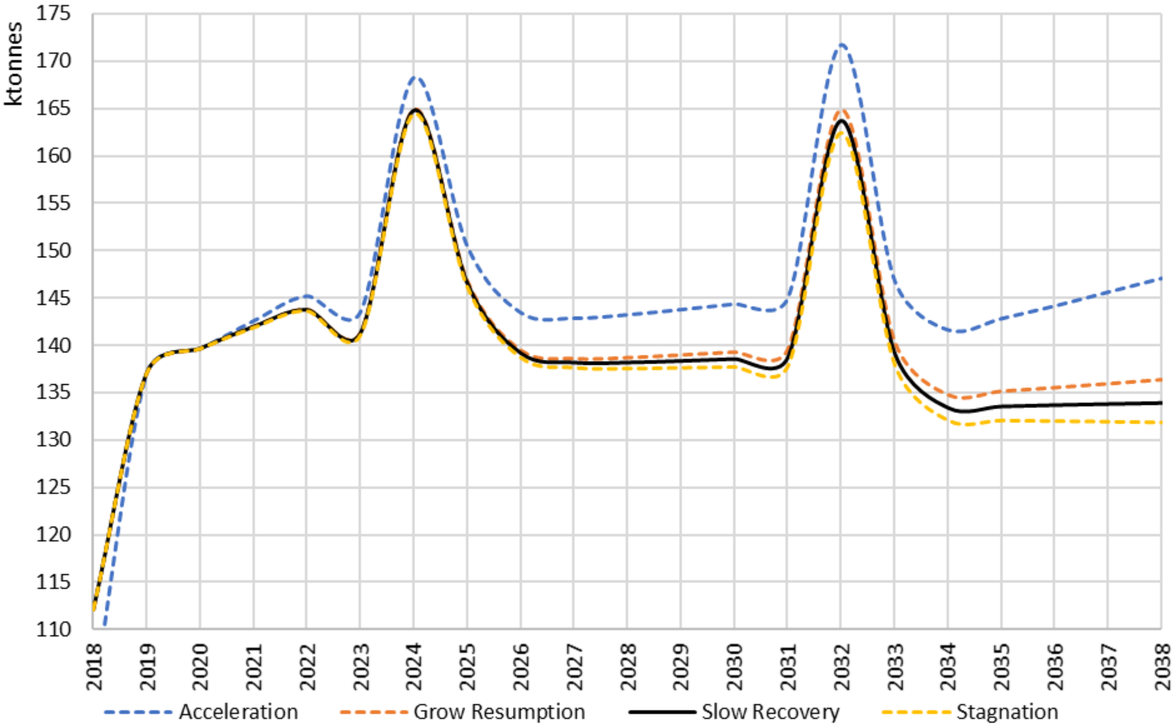


Figure 37: MSW waste collection scenarios.

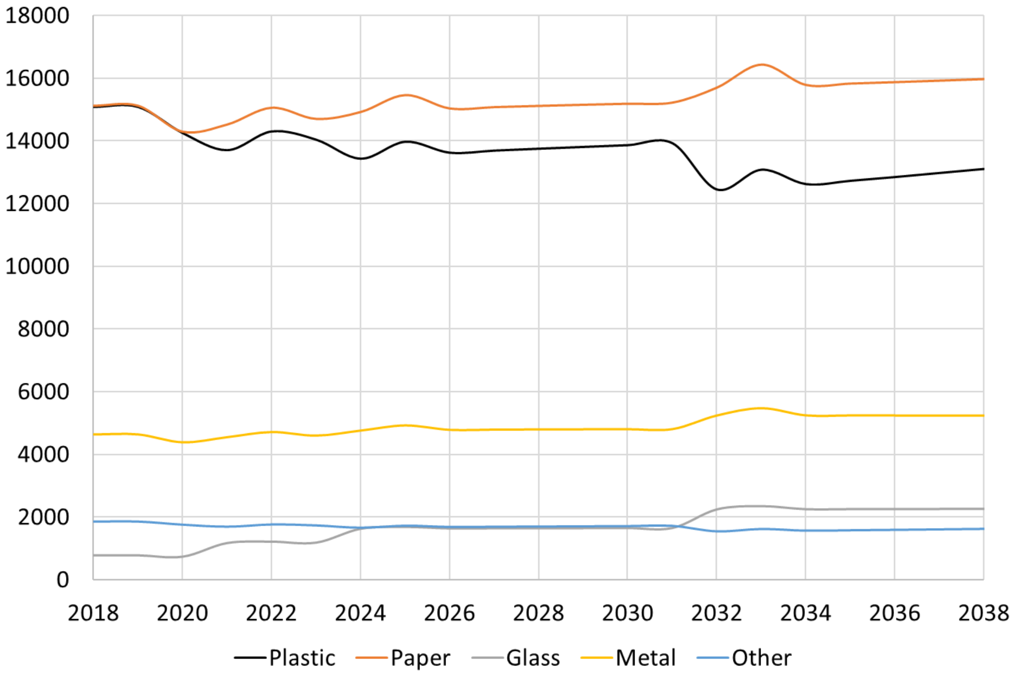


Figure 38: Evolution of replacement of plastics by paper, metal and glass.

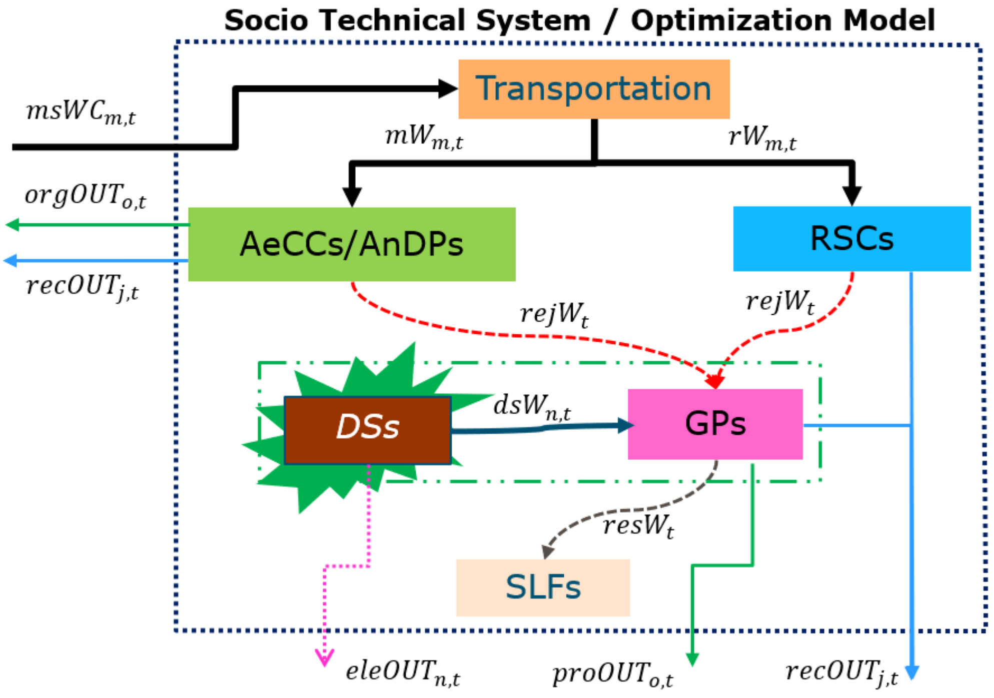


Figure 39: Concetual model of the IMWSM network.

model is applied to all scenarios. Since the outputs of the SD are aggregated for the whole Norte Pioneiro, each municipality population was divided by the total population of the region, to find the corresponding fraction for each municipality, $popF_m$. Values for $popF_m$ for each municipality can be found in Table C1.

These fractions are multiplied by the organic, wasted and mixed recyclable collected through AMC, and the recyclable waste collected through SSC, to determine $mW_{m,t}$ and $rW_{m,t}$, the all-mixed and the SS collected waste for each municipality m at time t. This is represented in Equations 15 and 16, which connects the SD model to the optimisation model.

$$mW_{m,t} = \left(oW_t + wW_t + rW_t^{AMC}\right) \times popF_m, \qquad \forall m,t \tag{15}$$

$$rW_{m,t} = rW_t^{SSC} \times popF_m \qquad \forall m,t \tag{16}$$

Figure 39 represents the flow diagram within the waste management network (the STS) by the dotted square, which is later optimised. $msWC_{m,t}$ represents all the waste collected in municipality m and time t entering the waste network, transported from the municipalities to the processing facilities. $rW_{m,t}$ is transported to the Recyclables Sorting Centres (RSCs), separated by each recyclable type, producing $recOUT_{j,t}$. The rejected portion of the recyclables, $rejW_t$, is sent for gasification.

The all-mixed stream $mW_{m,t}$ is directed to organic waste processing facilities, which

Waste Type	Fraction (kg/kg)
Recyclables	0.286
Plastic	0.170
Paper	0.075
Metal	0.028
Glass	0.013
Rest of the Waste (Fines, wood, . . .)	0.714

Table 13: Composition of Mined Waste. Source: Jones et al. (2013).

can be of two types: Aerobic Composting Centres (AeCC) and Anaerobic Digestion Plants (AnDP). Both facility types produce two outputs: $recOUT_{j,t}$ - recyclables sorted from the mixed waste, where j is the recyclable type, and $orgOUT_{o,t}$, where o is the output type, as defined in Table 9. Rejections from processing organic, recyclable waste, along with the entire wasted waste portion, make up the rejected waste flow, $rejW_t$, sent for the Gasification Plants (GPs).

The dashed-double-dot square inside the diagram represent the regeneration sub-network, consisting of the degraded sites (DSs) and the GPs. Waste landfilled from the DS n is mined and sent for the gasification plants, $dsW_{n,t}$, where the recyclables are sorted, outputting $recOUT_{j,t}$. Table 13 contains the waste fractions considered for the mined waste, based in Jones et al. (2013). Recyclables consist of a much smaller fraction in mined waste; the major part consisting of fines, therefore eliminating the need for an “other" recyclables category. The rejected part of the mined waste goes to gasification, together with the rejected waste from AeCCs, AnDPs and RSCs, outputting $proOUT_{o,t}$.

The residual waste from the gasification process, $resW_t$, is landfilled in Sanitary Landfills (SLFs). Currently, there are operational SLFs in the Norte Pioneiro region, and as performed with the RSCs, they are also included in the model. The residual waste, ashes, can also be used as raw material for the production of cement used in public constructions, as part of another strategy from PERS to divert waste from landfilling. Finally, if the DS n is transformed into a solar farm, it produces electricity, represented by flow $eleOUT_{n,t}$.

Resilience principles adopted for the conceptual model of the waste network are: Flexibility in Sourcing, as multiple municipalities providing waste are considered; Flexibility in Order - multiple outputs are produced by different process options; Capacity - a reserve capacity of 5% of total capacity is determined; Anticipation - through waste generation forecasting; and Adaptability, which is deployed in the optimisation model, as the ability to change the waste network configuration according to these changes. Considering the resilience of the surrounding

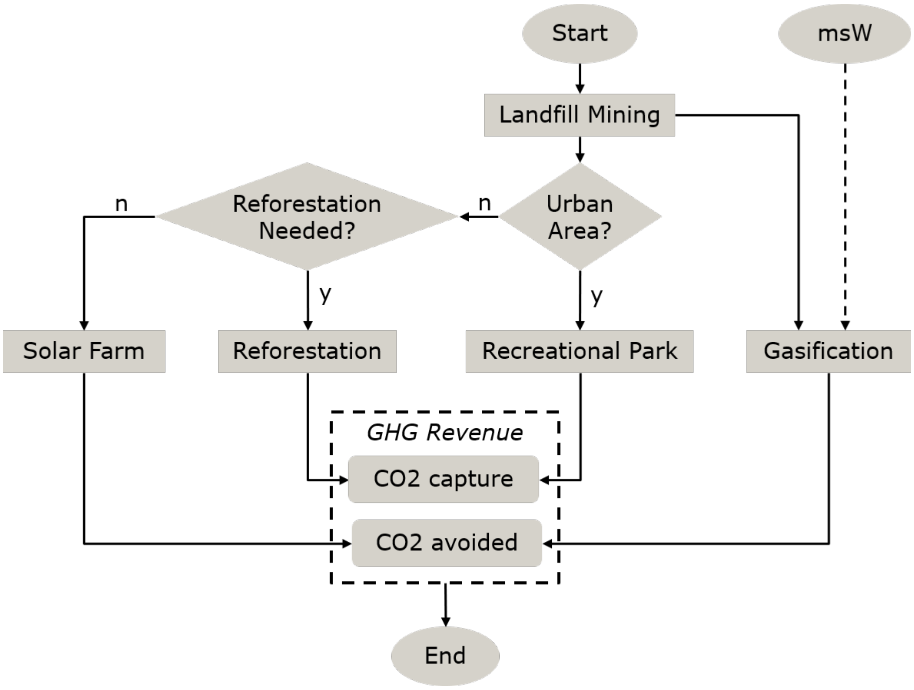


Figure 40: Flowchart to choose the regeneration strategy for each degraded site.

SES, or the region of NP, the following paragraphs describe how regeneration strategies were chosen, for each degraded site.

4.2.3.3 REGENERATION STRATEGIES FOR DEGRADED SITES

To define the regeneration strategies for the degraded sites, the surrounding context of each site was taken under consideration. Regeneration is performed in two steps: waste mining - prior to site regeneration, the waste inside the area is mined and sent to gasification -, and regeneration. Three strategies are defined: transformation into a recreational park, a solar farm or into a reforested area.

If the degraded site is located in an urban area, building a recreational park that captures CO_2 brings benefits to quality of life of the neighbours (SIMIS et al., 2016). If it is not in an urban area and located in a municipality that is short on forested areas, reforestation is the strategy selected, leading to GHG capturing. If the municipality cultivates reforested areas and/or original forests, the degraded site is transformed in a solar farm for clean electricity production, avoiding GHG emissions. A decision flowchart representing these choices is presented in Figure 40. The Gasification plants can process both the mined waste and the MSW collected yearly. In Table 14, the 23 degraded sites identified are organised by region and strategy adopted. In total, reforestation strategy was determined to twelve sites, solar farms to six and recreational parks, to four sites.

Region	Reforestation	Solar Farms	Recreational Parks
R6	Assaí Cornélio Procópio Itambaracá Nova Santa Bárbara	Congonhinhas São Sebastião da Amoreira	Santa Mariana
R7	Abatiá Andirá Pinhalão Ribeirão do Pinhal Salto do Itararé Siqueira Campos Wenceslau Braz 1 Wenceslau Braz 2	Ibaiti Jacarezinho 2 Jacarezinho 4 Jacarezinho 5	Carlópolis Jacarezinho 1 Jacarezinho 3

Table 14: Sites grouped by micro region and regeneration strategy.

With the waste management network conceptualised, the interactions with the SES and the regeneration strategies defined, the step of performance optimisation is developed, described in the next section.

4.2.4 PERFORMANCE OPTIMISATION

The supply network is optimised for the capacitated location-allocation problem - where the location of facilities with a limited capacity and allocation of flows for each facility are determined. The four waste generation scenarios are considered, for two maximisation strategies: maximisation of profit and maximisation of net GHG savings - the metrics chosen to measure the sustainable performance of the network. A Multi-Scenario, Multi-Period, Multi-Objective, Mixed Integer Linear Programming (MS-MP-MO-MILP) model was developed according to the sequence illustrated in Figure 41.

In an iterative process, the conceptual model (see Figure 39) is used in the elaboration of a mathematical model, solved computationally, outputting (i) network topology, (ii) environmental and economic performance and (iii) ENA results for quantification of resilience. Network topology is defined by (i) the types of opened facilities (ii), the location of each facility, (iii) the moment each facility should open and/or close, (iv) allocation of current and mined waste flows, and (v) the time each degraded site is regenerated, for each year in the 21-year period. Economic Performance is the network global profit for all 21 periods between 2018 and 2038, defined by the total revenues (it is assumed that all the outputs produced are sold) subtracted from the Operational Expenditures (OPEX) – consisting of fixed (30% of the total costs) and variable costs (70% of the total) -, and Capital Expenditures (CAPEX), i.e., investments and closing costs.

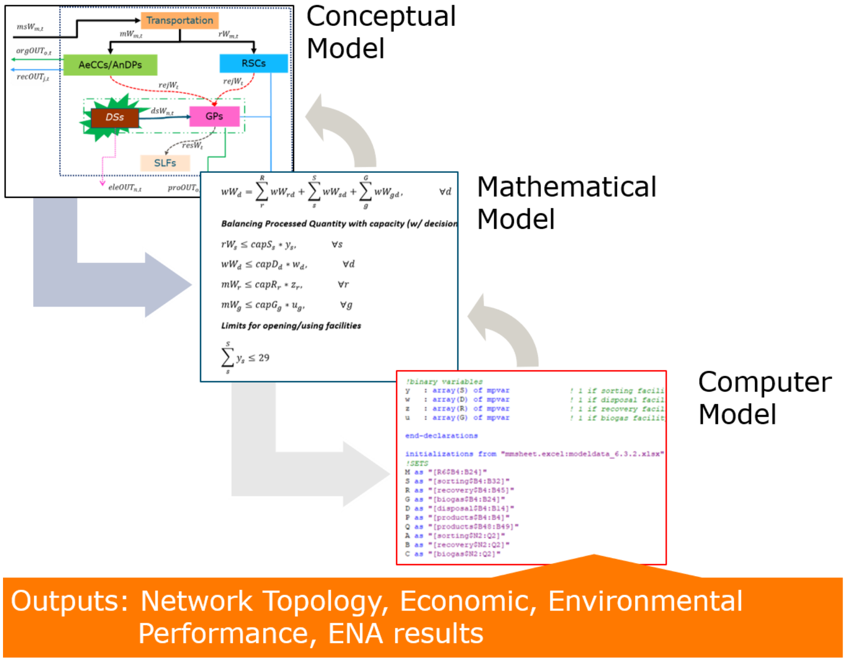


Figure 41: Optimisation model development sequence.

Environmental performance is approached in a similar way as the economic: “revenues” are the avoided GHG emissions from (i) replacing recyclables by virgin material, (ii) replacing fertilisers by compost and digestate, and (iii) replacing electricity supplied by the distribution system from electricity produced within the system. GHG emissions are the “expenditures", divided in emissions related with operations (OGEM), categorised in “fixed”, from running a facility (assumed as 10% of the total emissions) and “variable” emissions related to the production volume, assumed as 90%. Emissions from the construction of a facility are considered “capital" emissions (CAGEM), and emissions from closing a facility are considered negligible. Degraded sites transformed in recreational parks or reforested contribute for the “revenues" with captured GHG.

The Ecosystem Network Analysis is implemented and used to understand the balance between resilience and performance. Total development power, Relative Ascendency and Endurability are calculated for each solution provided by the model, allowing the comparison of resilience among the network configurations. The mathematical model is described next.

4.2.4.1 MATHEMATICAL MODEL

First, Sets, Parameters and Variables are listed, followed by the objective functions. All the values for the Parameters are reported in Appendix C.

SETS

H	Set of disposed waste types
I	Set of collected/transported waste types
J	Set of recyclable types
K	Set of facility types (RSC, small/big AeCC's, AnDP's, GP's, SLF's)
L	Set of existing recyclables sorting centres (eRSCs)
M	Set of Municipalities
N	Set of degraded sites to be recovered (DSs)
O	Set of output products
Q	Set of existing landfills (eSLFs)
$NY = 21$	Number of years in the horizon (time periods)
$T = 1, \ldots, NY$	Set of time periods (years)

PARAMETERS

$mW_{m,t}$	Mixed Waste collected in municipality m at time t [tonnes]
$rW_{m,t}$	Recyclable Waste collected in municipality m at time t [tonnes]
$gwF_{h,t}$	Disposed waste fraction type i at time t [tonnes/tonne]
$procdswF$	Processed waste fraction from mined waste [tonnes/tonne]
$rdswF$	Recyclable fraction in the degraded site waste [tonnes/tonne]
$mswrecF_{j,t}$	Recyclables fraction type j from mixed waste at time t [tonnes/tonne]
$dswrecF_{j}$	Recyclables fraction type j from mined waste [tonnes/tonne]
$convR_{o,k}$	Conversion rate of mW of facility type k into output o [tonnes/tonne]
$sortR_{k,t}$	Sorting rate of facility type k at time t [tonnes/tonne]
$wwconvR_{o,t}$	Conversion rate of rejected waste into output o at time t [tonnes/tonne]
$gpsortR$	Sorting Rate of a GP [tonnes/tonne]
$sortRCF_{l,t}$	Sorting rate of RSC l at time t [tonnes/tonne]
cap_{k}	Processing capacity of facility type k [tonnes/year]
$capRSC_{l}$	Capacity of existing RSC l [tonnes/year]
$cpcSLF_{q}$	Total capacity of existing SLF q [tonnes]
$capSLF$	Total capacity of a new SLF [tonnes]
$wTP_{i,k}$	Waste processed type i by facility k [tonnes]
$link_{k,k'}$	Allowed connections between facilities in the network [binary]
$IdsINV_{n}$	Initial degraded site waste inventory for site n [tonnes of waste]
$wlcSLF_{q}$	Current (initial) waste load in landfill q [tonnes]
$d_{m,m'}$	Distance from municipality m to municipality m' [km]
$d_{n,m}$	Distance from degraded site n to municipality m [km]

$d_{m,l}$	Distance from municipality m to existing RSC l [km]
$d_{l,m}$	Distance from RSC l to municipality m [km]
$d_{m,q}$	Distance from municipality m to existing SLF q [km]
$transCOST$	Transportation cost of 1 tonne of waste per km [BRL/tonne/km]
$varCOST_k$	Variable cost for processing waste at facility type k [BRL/tonne]
$fixCOST_k$	Fixed cost of facility type k [BRL/year]
$crscCOST_l$	Cost for sorting waste at RSC l [BRL/tonne]
$cslfCOST_q$	Cost for landfilling waste at SLF q [BRL/tonne]
$varCOST_n$	Variable cost for regenerated site n [BRL/tonne]
$fixCOST_n$	Fixed cost for regenerated site n [BRL/tonne]
$capex_k$	Investment cost (CAPEX) for opening a facility type k [BRL/unit]
$capex_n$	Investment cost for regenerating a degraded site n [BRL/unit]
$closCOST_k$	Cost for closing facility k [BRL/unit]
$recP_j$	Price of sorted recyclable waste type j [BRL/tonne]
$outP_o$	Price of output o [BRL/output unit]
REV_n	Revenues from regenerated site n [BRL/year]
$transGEM$	GHG emissions from transportation of 1 tonne of waste per km [kgCO$_{2eq}$/tonne/km]
$sortGEM$	GHG emissions from sorting at AeCC/AnDP/GP [kgCO$_{2eq}$ /tonne]
$varGEM_k$	"variable" GHG emissions from processing waste at facility k [kgCO$_{2eq}$ /tonne]
$fixGEM_k$	"fixed" GHG emissions from facility k [kgCO$_{2eq}$ /year]
$varGEM_n$	"variable" GHG emissions from regenerated site n [kgCO$_{2eq}$ /year]
$fixGEM_n$	"fixed" GHG emissions from regenerated site n [kgCO$_{2eq}$ /year]
$crscGEM_l$	GHG emissions from waste sorting at RSC l [kgCO$_{2eq}$ /tonne]
$cslfGEM$	GHG emissions from waste disposal [kgCO$_{2eq}$ /tonne]
$orgGEM$	GHG emissions from raw organic waste disposal [kgCO$_{2eq}$ /tonne]
$cagem_k$	GHG emissions from opening facility type k [kgCO$_{2eq}$ /unit]
$cagem_n$	GHG emissions from regenerating degraded site n [kgCO$_{2eq}$ /unit]
$recGAV_j$	Avoided GHG emissions from using recyclable type j [kgCO$_{2eq}$/tonne]
$outGAV_o$	Avoided GHG emissions from using output o [kgCO$_{2eq}$/tonne]
GAV_n	Avoided/captured GHG emissions per regenerated site n [kgCO$_{2eq}$/year]
$jobs_k$	Number of jobs created by facility type k opened [jobs/fac. type]
$rmwrecOUT_{j,k,m,t}$	Output of recyclables type j from processing mixed waste in facility type k at municipality m at time t [tonnes/year]

$rwrecOUT_{j,k,m,t}$	Output of recyclables type *j* from processing sorted recyclable waste in facility type *k* at municipality *m* at time *t* [tonnes/year]
$dswrecOUT_{j,k,m,t}$	Output of recyclables type *j* from processing mined waste in facility type *k* at municipality *m* at time *t* [tonnes/year]
$rwrecOUTc_{j,l,t}$	Output of recyclables type *j* from processing sorted recyclable waste in existing RSC *l* at time *t* [tonnes/year]
$orgOUT_{o,k,m,t}$	Output of organic product type *o* from processing mixed waste in facility type *k* at municipality *m* at time *t* [tonnes/year]
$proOUT_{o,k,m,t}$	Output of organic product type *o* from processing rejected waste in facility type *k* at municipality *m* at time *t*
$TREX_t$	Expenditures from transportation at time *t* [BRL/year]
$TGEM_t$	GHG emissions from transportation at time *t* [BRL/year]
$clI_{q,t}$	Inventory of existing SLFs *q* at time *t* [tonnes/year]
$dsI_{n,t}$	Inventory of mined waste at site *n* at time *t* [tonnes/year]

VARIABLES

$X_{i,m,k,m',t}$	Waste type *i* transported from municipality *m* to facility type *k* in municipality *m′* at time *t* [tonnes/year]
$Xc_{m,l,t}$	Recyclable waste transported from municipality *m* to RSC *l* in municipality *m* at time *t* [tonnes/year]
$Y_{k,m,k',m',t}$	Rejected/Residual waste from fac. type *k* at munic. *m* transported to facility type *k′* in municipality *m′* at time *t* [tonnes/year]
$Yc_{l,k,m,t}$	Rejected Waste from RSC *l* transported to facility type *k* in municipality *m* at time *t* [tonnes/year]
$Zc_{k,m,q,t}$	Rejected Waste from facility type *k* in municipality *m* to current SLF *q* at time *t* [tonnes/year]
$W_{n,k,m,t}$	Mined waste transported from degraded site *n* to facility type *k* in municipality *m* at *t* [tonnes/year]
$A_{k,m,t}$	Decision to open a facility type *k* in municipality *m* at time *t* [binary]
$B_{k,m,t}$	Decision to operate a facility type *k* in municipality *m* at time *t* [binary]
$C_{k,m,t}$	Decision to close a facility type *k* in municipality *m* at time *t* [binary]
$Dm_{n,t}$	Decision to mine degraded site *n* at time *t* [binary]
$Dr_{n,t}$	Decision to recover degraded site *n* at time *t* [binary]
$Do_{n,t}$	Decision to operate recovered site *n* at time *t* [binary]

$$\max \quad \sum_{j}^{J}\sum_{t}^{T}\left[\left(\sum_{k}^{K}\sum_{m}^{M} rmwrecOUT_{j,k,m,t} + rwrecOUT_{j,k,m,t} + dswrecOUT_{j,k,m,t}\right) + \sum_{l}^{L} rwrecOUTc_{j,l,t}\right] \times recP_{j} \tag{17a}$$

$$+\sum_{o}^{O}\sum_{k}^{K}\sum_{m}^{M}\sum_{t}^{T}\left(orgOUT_{o,k,m,t} + proOUT_{o,k,m,t}\right) \times outP_{q} + \sum_{t}^{T}\sum_{n}^{N} Do_{n,t} \times REV_{n} \tag{17b}$$

$$-\sum_{t}^{T} TREX_{t} - \sum_{m}^{M}\sum_{l}^{L}\sum_{t}^{T} Xc_{m,l,t} \times crscCOST_{l} - \sum_{k}^{K}\sum_{m}^{M}\sum_{q}^{Q}\sum_{t}^{T} Zc_{k,m,q,t} \times cslfCOST_{q} \tag{17c}$$

$$-\sum_{k\prime}^{K}\sum_{m}^{M}\sum_{t}^{T}\left(\sum_{i}^{I}\sum_{m}^{M} X_{i,m,k\prime,m\prime,t} + \sum_{k}^{K}\sum_{m}^{M} Y_{k,m\prime,k\prime,m\prime\prime,t} + \sum_{l}^{L} Yc_{l,k\prime,m\prime,t} + \sum_{n}^{N} W_{n,k\prime,m\prime\prime,t}\right) \times varCOST_{k} \tag{17d}$$

$$-\sum_{k}^{K}\sum_{m}^{M}\sum_{t}^{T} A_{k,m,t} \times capex_{k} - \sum_{k}^{K}\sum_{m}^{M}\sum_{t}^{T} B_{k,m,t} \times fixCOST_{k} - \sum_{k}^{K}\sum_{m}^{M}\sum_{t}^{T} C_{k,m,t} \times closCOST_{k} \tag{17e}$$

$$-\sum_{t}^{T}\sum_{n}^{N} Dr_{n,t} \times capex_{n} - \sum_{t}^{T}\sum_{n}^{N} Do_{n,t} \times fixCOST_{n} \tag{17f}$$

The objective function for maximisation of economic performance is presented in Equation 17. Term 17a is, respectively, the sum of all recyclable outputs from facilities that process mixed waste, single-stream recyclables and mined waste (between parenthesis), and existing RSCs, multiplied by the selling price of each recyclable type. Term 17b sums the revenues obtained from outputs of organic waste processing with the waste processed by GPs (quantity produced multiplied by outputs price) with the revenues obtained from the regenerated sites, determined by values from Table C4. Term 17c contains the transportation costs, the processing costs of existing RSCs and landfill cost on existing SLFs. Term 17d is the processing cost for all the waste flows within the system. Term 17e consist of the costs for opening, operating and closing facilities. Finally, Term 17f, holds the cost for recovering and operating regenerated sites.

$$\max \quad \sum_{j}^{J}\sum_{t}^{T}\left[\left(\sum_{k}^{K}\sum_{m}^{M} rmwrecOUT_{j,k,m,t} + rwrecOUT_{j,k,m,t} + dswrecOUT_{j,k,m,t}\right) + \sum_{l}^{L} rwrecOUTc_{j,l,t}\right] \times recGAV_{j} \tag{18a}$$

$$+\sum_{o}^{O}\sum_{k}^{K}\sum_{m}^{M}\sum_{t}^{T}\left(orgOUT_{o,k,m,t} + proOUT_{o,k,m,t}\right) \times outGAV_{q} + \sum_{t}^{T}\sum_{n}^{N} Do_{n,t} \times GAV_{n} \tag{18b}$$

$$-\sum_{t}^{T} TGEM_{t} - \sum_{m}^{M}\sum_{l}^{L}\sum_{t}^{T} Xc_{m,l,t} \times crscGEM_{l} - \sum_{k}^{K}\sum_{m}^{M}\sum_{q}^{Q}\sum_{t}^{T} Zc_{k,m,q,t} \times cslfGEM_{q} \tag{18c}$$

$$-\sum_{k'}^{K}\sum_{m}^{M}\sum_{t}^{T}\left(\sum_{i}^{I}\sum_{m}^{M} X_{i,m,k',m',t} + \sum_{k}^{K}\sum_{m}^{M} Y_{k,m',k',m'',t} + \sum_{l}^{L} Yc_{l,k',m',t} + \sum_{n}^{N} W_{n,k',m'',t}\right) \times varGEM_{k} \tag{18d}$$

$$-\sum_{k}^{K}\sum_{m}^{M}\sum_{t}^{T} A_{k,m,t} \times cagem_{k} - \sum_{k}^{K}\sum_{m}^{M}\sum_{t}^{T} B_{k,m,t} \times fixGEM_{k} - \sum_{t}^{T}\sum_{n}^{N} Dr_{n,t} \times cagem_{n} - \sum_{t}^{T}\sum_{n}^{N} Do_{n,t} \times fixGEM_{n} \tag{18e}$$

The objective function for environmental performance maximisation is presented in Equation 18. It follows the same sequence as in Equation 17: term 18a is the avoided GHG with recyclable outputs produced from mixed, mined and recyclable waste, for opened facilities and existing RSCs. Term 18b shows the avoided GHG from organic and rejected waste outputs. Term 18c consists of the GHG emissions from transportation, processing on existing RSCs and disposal on SLFs. Term 18d defines the GHG emissions from all waste processed, and term 18d, the capital GHG emissions from opening and running facilities, recovering and operating recovered sites. GHG emissions from closing facilities are considered negligible.

Subject to:

$$rmwrecOUT_{j,k,m',t} = \sum_{m'}^{M} X_{i,m,k,m',t} \times gwF_{h,t} \times sortR_{k,t} \times mswrecF_{j,t}, \qquad \forall j,k,m',t,i = mixW, h = rWF \tag{19}$$

$$rwrecOUT_{j,k,m',t} = \sum_{m'}^{M} X_{i,m,k,m',t} \times gwF_{h,t} \times sortR_{k,t} \times mswrecF_{j,t}, \qquad \forall j,k,m',t,i = recW, h = rWF \tag{20}$$

$$dswrecOUT_{j,k,m,t} = \sum_{n}^{N} W_{n,k,m,t} \times rdswF \times dswrecF_{j} \times gpsortR, \qquad \forall j,m,t,k = GP \tag{21}$$

$$rwrecOUTc_{j,l,t} = \sum_{m}^{M} Xc_{m,l,t} \times sortRCF_{l,t} \times mswrecF_{j,t}, \qquad \forall j,l,t \tag{22}$$

$$orgOUT_{o,k,m',t} = \sum_{m}^{M} X_{i,m,k,m',t} \times gwF_{h,t} \times wTP_{i,k} \times convR_{o,k}, \qquad \forall o,k,m',t,i = mixW, h = oWF \tag{23}$$

Equation 19 defines the recyclables output from sorting the mixed waste, by type j from facility type k, as the product of: the sum of flows sent to facility k, with the recyclable waste fraction at time t, with the sorting rate for that facility at time t, with the fraction of recyclable type j. Equation 20 is similar to 19, but for flow SS (rW). Equation 21 defines the recyclables output as the product between the sum of the mined waste sent to gasification, with the recyclable fraction of the mined waste, with the recyclable type j fraction, with the sorting rate of the GP. Equation 22 defines the output of recyclables of existing RSCs as the product between the sum of flows sent to RSC l (Xc), with the sorting rate of RSC l, with the recyclable type j fraction. Equation 23 defines the outputs of organic waste processing from facilities k as the product between the sum of the waste coming from the municipalities (X), with the respective organic waste fraction (index h) at time t, with the waste type processed, with the conversion rate of organic waste into product o.

$$proOUT_{o,k',m',t} = \left(\sum_{k}^{K} \sum_{m}^{M} Y_{k,m,k',m',t} \times link_{k,k'} + \sum_{l}^{L} Yc_{l,k',m',t} + \sum_{n}^{N} W_{n,k',m',t} \times procdswF \right) \times wwconvR_{o,t}, \quad \forall i,m',o,t,k' = GP \tag{24}$$

Equation 24 defines the outputs of the gasification plants as the product between: the sum of the flows from facilities k (with the exception of GPs), multiplied by the link among facilities - a matrix defining which facility can send flow to which, defined by Equation C3, plus the sum of the flows coming from the existing RSCs, plus the sum of the mined waste multiplied by the fraction of the mined waste that goes to gasification (non recyclable), and the conversion rate of the gasification, for each output o at time t. In this case, the dimension t is required due to the ashes being changed from rejected output to usable output with economic value, as detailed in Table C8.

$$mW_{m,t} \geq \sum_{k}^{K} \sum_{m\prime}^{M} X_{i,m,k,m\prime,t}, \qquad \forall m,t,i = mixW \tag{25}$$

$$rW_{m,t} \geq \sum_{m\prime}^{M} X_{i,m,k,m\prime,t} + \sum_{l}^{L} Xc_{m,l,t}, \qquad \forall m,t,k,i = recW \tag{26}$$

Inequality 25 defines the mixed waste balance from municipality m to facility type k in municipality $m\prime$, at time t - linked with index $i = mixW$. Inequality 26 defines the recyclable waste balance from municipality m to be transported either to the existing RSCs l (flow Xc) or to new ones (flow X, with i=$recW$), at time t.

$$A_{k,m,t}, B_{k,m,t}, C_{k,m,t} = \begin{cases} 1, \; if \; facility \; is \; open/run/close \\ 0 \; otherwise \end{cases}, \qquad \forall k,m,t \tag{27}$$

$$Dm_{n,t}, Dr_{n,t}, Do_{n,t} = \begin{cases} 1, \; if \; DS \; is \; mined/regen./op. \\ 0 \; otherwise \end{cases}, \qquad \forall n,t \tag{28}$$

Condition 27 defines values for binary decision variables linked with the decision of opening (A), running (B) or closing (C) a facility type k at municipality m at time t. Condition 28 defines the regeneration of degraded sites: Dm is 1 if the site n is being mined at time t, Dr if a regeneration strategy was applied and the site is recovered; and Do, if the regenerated site is operational.

$$\sum_{t}^{t\prime} A_{k,m,t\prime+1-t} \geq B_{k,m,t\prime}, \qquad \forall k,m,t\prime \tag{29}$$

$$A_{k,m,t} - C_{k,m,t} = B_{k,m,t} - B_{k,m,t-1}, \qquad \forall k,m,t > 1 \tag{30}$$

$$\sum_{t}^{T} A_{k,m,t} \leq 1, \qquad \forall k,m \tag{31}$$

$$\sum_{t}^{T} B_{k,m,t} \leq NY, \qquad \forall k,m \tag{32}$$

$$\sum_{m}^{M} A_{k,m,t} \leq nM, \qquad \forall k,t \tag{33}$$

Equations 29 to 33 define conditions for opening, running and closing facilities. 29 restricts the model to only run a facility after it is opened. 30 links decisions of opening, closing and running facilities: if a facility is opened, then it must be running; if its closed, it was running in $t-1$. 31 limits that a facility type k can be opened at municipality m only once during the entire 21-year period, avoiding that the model opens and closes a same facility in the same municipality. 32 limits the number of running years to be, at most, the number of years in the period, 21, while 33 limits the maximum number of facilities to be opened as less or equal to the number of municipalities, nM.

$$\begin{aligned}\sum_{k\prime}^{K}\sum_{m\prime\prime}^{M} Y_{k,m\prime,k\prime,m\prime\prime,t} = {} & orgOUT_{o,k,m\prime,t} + \sum_{m}^{M} X_{i=mixW,m,k,m\prime,t} \times gwF_{h=wWF,t} \\ & + \sum_{m}^{M} X_{i=recW,m,k,m\prime,t} \times (1 - sortR_{k,t}) \\ & + \sum_{m}^{M} X_{i=mixW,m,k,m\prime,t} \times gwF_{h=rWF,t} \times (1 - sortR_{k,t}), \\ & \qquad \forall k,m\prime,t,o = rejected,k\prime = GP\end{aligned} \tag{34}$$

Equation 34 defines the sum of the flows sent to GPs as the sum of the rejected outputs from the RSCs, AnDPs and AeCCs, plus the wasted waste, plus the rejected recyclables from sorting recyclable waste, plus the rejected recyclables from sorting mixed waste.

$$\sum_{m}^{M} Xc_{m,l,t} \times (1 - sortRCF_{l,t}) = \sum_{m'}^{M} Yc_{l,k,m',t}, \qquad \forall l,t,k = GP \tag{35}$$

$$\sum_{m}^{M} Xc_{m,l,t} \leq 0.95 \times capcRSC_{l}, \qquad \forall l,t \tag{36}$$

$$\sum_{k}^{K}\sum_{m}^{M} Y_{k,m,k',m',t} \leq cap_{k'} \times B_{k',m',t}, \qquad \forall k',m',t \tag{37}$$

$$\sum_{k}^{K}\sum_{m}^{M}\sum_{t}^{T} Y_{k,m,k',m',t} \leq 0.95 \times cap_{k'}, \qquad \forall k' = SLF, m' \tag{38}$$

Equation 35 determines that the sum of the rejected waste from the existing RSCs is equal to the sum of the flows going from these existing RSCs to the GPs. Equation 36 limits the recyclable waste to be sorted at the existing RSC l to 95% of its capacity ($capcRSC_l$). Equation 37 imposes a SLF to be operational if waste is transported to a SLF at municipality m at time t. The total waste landfilled cannot exceed 95% of its capacity, as defined in Equation 38.

$$IdsINV_{n} \geq \sum_{m}^{M}\sum_{t}^{T} W_{n,k,m,t}, \forall n, k = GP \tag{39}$$

Equation 39 establishes that the total waste mined through the 21-year period is smaller or equal to the total initial quantity of waste in the degraded site n.

$$proOUT_{o,k,m,t} = \sum_{m}^{M} Y_{k,m,k',m',t} + \sum_{q}^{Q} Zc_{k,m,q,t}, \forall k = GP, k' = SLF, m', t, o = rejected \tag{40}$$

Equation 40 balances the residual waste from the gasification plants (rejected output) with the flows to the existing landfill sites (Zc) plus the opened SLFs (Y).

$$clI_{q,t} = \begin{cases} wlcSLF_{q} + \sum_{k}^{k}\sum_{m}^{M} Zc_{k,m,q,t} \leq cpcSLF_{q}, & \forall q, t = 1 \\ clI_{q,t-1} + \sum_{k}^{k}\sum_{m}^{M} Zc_{k,m,q,t} \leq cpcSLF_{q}, & \forall q, t \geq 1 \end{cases} \tag{41}$$

$$dsI_{n,t} = \begin{cases} IdsINV_{n} - \sum_{m}^{M} W_{n,k,m,t}, & \forall n, k = GP, t = 1 \\ dsI_{n,t-1} - \sum_{m}^{M} W_{n,k,m,t}, & \forall n, k = GP, t > 1 \end{cases} \tag{42}$$

Equations 41 define the waste inventory at existing landfill q at time t. In the first period, the inventory is equal to the initial inventory ($wlcSLF_q$), plus the sum of the waste transported from facility k at municipality m to landfill q. This inventory must be less or equal to the landfill limit, $cpcSLF_q$. From the second period onwards, the inventory will be the inventory of the previous year $(t-1)$, plus the waste transferred at year t. Equations 41 operate similarly for the inventory of the mined waste, only that the inventory now is decreasing with the waste being mined. In the first year, it is equal to the initial stock $(IdsINV_n)$ minus the sum of the mined waste transported to the GPs, W.

$$dsI_{n,t} \leq M \times Dm_{n,t}, \qquad \forall n, t > 1 \tag{43}$$

$$Dr_{n,t} = Do_{n,t} - Do_{n,t-1}, \qquad \forall n, t > 1 \tag{44}$$

$$Dr_{n,t} = Dm_{n,t-1}, \qquad \forall n, t > 4 \tag{45}$$

$$\sum_{t}^{T} Dr_{n,t} = 1, \qquad \forall n \tag{46}$$

$$\sum_{t}^{T} Do_{n,t} \geq 10, \qquad \forall n \tag{47}$$

Equation 43 imposes that *Dm* must be one, as long as the degraded site is being mined, using the *Big M* technique. Equation 44 links *Dr*, for the regeneration, and *Do*, for operating the regenerated site. If the site was not regenerated, than it cannot be previously operated. Equation 46 obligates the model to regenerate every degraded site *n*, while 47, to do it with at least 10 years remaining in the 21-year period.

$$0.95 \times cap_k \times B_{k,m,t} \geq \begin{cases} \sum_m^M X_{i,m,k,m',t}, & \forall k,m,t,i = mixW, recW \\ \sum_k^K \sum_m^M Y_{k,m,k',m',t} + \sum_l^L Yc_{l,k',m',t} + \sum_n^N W_{n,k',m',t}, & \forall k,m,t,k' = GP \end{cases} \tag{48}$$

Equation 48 defines the processing quantities for facilities k to be less or equal to its capacity, linking it with the binary variable for operating a facility, B. For mixed and recyclable waste processing facilities, the sum of all flows coming from the municipalities cannot exceed 95% of its capacity. For the GPs, its the sum of flows coming from the other type k facilities (Y) plus the flows coming from the existing RSCs (Yc), plus the sum of the mined waste flows coming from the degraded sites, W, that must be less or equal to 95% of its capacity.

$$\begin{aligned} TREX_t = \Bigg[& \sum_k^K \sum_m^M \sum_{m'}^M \sum_i^I X_{i,m,k,m',t} \times d_{m,m'} + \sum_m^M \sum_l^L Xc_{m,l,t} \times d_{m,l} + \sum_k^K \sum_{m'}^M \sum_{m''}^M \sum_{k'}^K Y_{k,m',k',m'',t} \times d_{m',m''} \\ & + \sum_l^L \sum_{k'}^K \sum_{m''}^M Yc_{l,k',m'',t} \times d_{l,m''} + \sum_n^N \sum_{k'}^K \sum_{m''}^M W_{n,k',m'',t} \times d_{n,m''} + \sum_{k'}^K \sum_{m''}^M \sum_q^Q Zc_{k',m'',q,t} \times d_{m,q} \Bigg] \times transCOST, \ \forall t \end{aligned} \tag{49}$$

$$\begin{aligned} TGEM_t = \Bigg[& \sum_k^K \sum_m^M \sum_{m'}^M \sum_i^I X_{i,m,k,m',t} \times d_{m,m'} + \sum_m^M \sum_l^L Xc_{m,l,t} \times d_{m,l} + \sum_k^K \sum_{m'}^M \sum_{m''}^M \sum_{k'}^K Y_{k,m',k',m'',t} \times d_{m',m''} \\ & + \sum_l^L \sum_{k'}^K \sum_{m''}^M Yc_{l,k',m'',t} \times d_{l,m''} + \sum_n^N \sum_{k'}^K \sum_{m''}^M W_{n,k',m'',t} \times d_{n,m''} + \sum_{k'}^K \sum_{m''}^M \sum_q^Q Zc_{k',m'',q,t} \times d_{m,q} \Bigg] \times transGEM, \ \forall t \end{aligned} \tag{50}$$

Finally, Equations 49 and 50 define the transportation costs and GHG emissions, as the product of the flows among facilities, with the distance between the municipalities exchanging the flows, with the unitary transportation cost, or GHG emissions.

4.2.4.2 COMPUTER MODEL

The computer model was developed with Xpress IVE Software 6.4 64-bit, in a computer with i5, 2.5GHz processor with 8GB of RAM and storage of 256GB SSD. The model for the whole region featured more than 2,8 million variables, and solutions achieved were not satisfactory, even after running for extended periods. The problem was divided considering regions R6 and R7, the four scenarios, two regions and two strategies - maximisation of profit and maximisation of net GHG savings -, resulting in 16 combinations. Several assumptions were made: all product outputs are considered to be sold, generating maximum revenue. Random variations are not considered: the model is deterministic. When a facility is opened in the model, no time delay is considered for building it. Values for GHG emissions and avoidance are taken from available literature, so careful is needed when reading and interpreting the model outputs. The solution method used was the dual simplex.

Solutions were achieved in a two-stage modelling runs: first, a preliminary solution is achieved running the model. This solution features a considerable optimality gap, and therefore it is used as a reference to narrow the solution space, which was performed in two ways: first, the variable X is forced to zero, according to the conceptual model, as defined in Equation 51. Second, the quantity and the types of facilities opened/closed to process the waste collected are limited according to Equations 52 and 53, limiting the total quantity of opened facilities to fifteen, and closed facilities to three, for the entire 21-year period. Equation 51 disables the opening, running and closing decisions for facilities type small Aerobic Composting Centre, Anaerobic Digestion Plants and Sanitary Landfills. Equations 55 to 57 limit the quantity of facilities type RSC, GP and bAeCC, respectively. Values for limits $\alpha, \beta, \gamma, \delta, \omega$ vary according to the region optimised, and are declared in Table 16.

$$\sum_{m}^{M}\sum_{m\prime}^{M} X_{i,m,k,m\prime,t} = 0, \qquad \forall i = mixW, k \in \{RSC, GP, SLF\}, t \tag{51}$$

$$\sum_{k}^{K}\sum_{m}^{M}\sum_{t}^{T} A_{k,m,t} \leq \alpha \tag{52}$$

$$\sum_{k}^{K}\sum_{m}^{M}\sum_{t}^{T} C_{k,m,t} \leq \beta \tag{53}$$

$$\sum_{m}^{M}(A_{k,m,t} + B_{k,m,t} + C_{k,m,t}) = 0, \qquad \forall k \in \{sAeCC, AnDP, SLF\}, t \tag{54}$$

Limit	Region	
	R6	R7
α	15	22
β	3	5
γ	5	5
δ	3	3
ω	7	12

Table 16: Limits for the quantity of opened and closed facilities.

$$\sum_{m}^{M} A_{k,m,t} \leq \gamma, \qquad \forall k = RSC, t \tag{55}$$

$$\sum_{m}^{M} A_{k,m,t} \leq \delta, \qquad \forall k = GP, t \tag{56}$$

$$\sum_{m}^{M} A_{k,m,t} \leq \omega, \qquad \forall k = bAeCC, t \tag{57}$$

After the solution space was narrowed, the problem reduced considerably in size. Region 6 problem contains now less than 650,000 variables, and Region 7, less than 840,000. After presolving, both problems decrease massively the size, with Region 6 remaining with 52,808, and Region 7, with 88,045.

For the generation of the Pareto frontier, the most probable scenario was chosen, SR, for region 6 - it was also not possible to achieve satisfactory Pareto solutions for region 7. To generate the curve, first the ε-constraint method was tried, but the software could not reach integer solutions within a satisfactory optimality gap, with a difference of around 100% between the best bound and the best solution achieved. Therefore, the weighted sum approach was used, which aggregates multiple objectives in a single, normalised objective function (JAKOB; BLUME, 2014). For this research, the normalisation was performed according to Equation 58, based in Jakob e Blume (2014).

$$f_i^{norm} = \frac{f_i - \max(f_i)}{\max(f_i) - \min(f_i)} \tag{58}$$

Where i is the objective being normalised, $\max(f_i)$ is the maximum value achieved from the optimisation of the single objective, and $\min(f_i)$ is the minimum value for this objective achieved from the optimisation of the other single objective - e.g., profit achieved in the strategy of maximisation of net GHG savings. The weighted sum maximisation objective can be calculated according to Equation 59. w_i are the weights assigned for each objective,

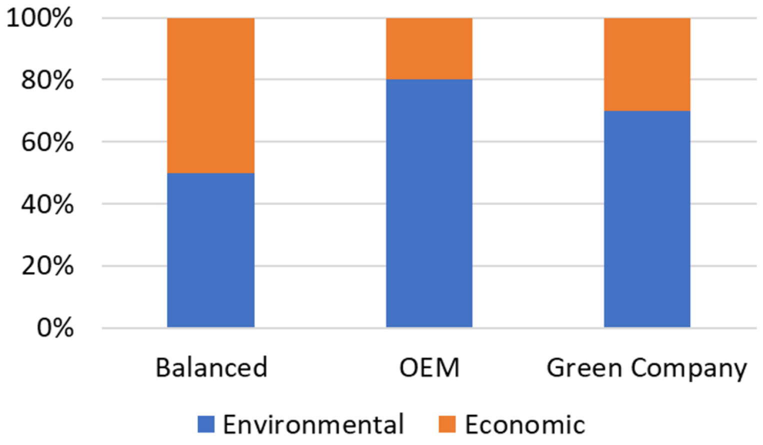


Figure 42: Weight distribution for the generation of Pareto Solutions.

which sum must equal to one.

$$\max \sum_{i=1}^{k} w_i f_i^{norm}, \quad \forall w_i > 0, \sum_{i=1}^{k} w_i = 1 \tag{59}$$

The weights were determined according to Stoycheva et al. (2018). Two extreme points are determined by the sinlg-objective maximisation of profit and net GHG, respectively. Three intermediate points were established: the first is defined using a balanced distribution of weights for both objectives. The second, "Original Equipment Manufacturer" (OEM), is mostly focused on profit, with a weight distribution of 80% on profit and 20% on net GHG. Last point, "Green Company", was defined from a 70% weight on net GHG, and 30% on profit. Figure 42 illustrates the three weight distributions. The Pareto frontier was plotted with solutions from max PROFIT and max net GHG strategies as the extreme points, together with the three intermediate solutions obtained through Equations 58 and 59.

The percentage of avoided landfill waste ($\%\ of\ AVlfW$) is calculated according to Equation 60, from the total waste landfilled in each scenario plus the non-processed recyclable waste by the IMSW network, $nprW_t$, plus the non-processed mixed waste by the IMSW network, $nprW_t$, divided by total waste entering the waste management network: mixed and recyclable waste collected yearly, plus the waste mined from the degraded sites. The avoided GHG emissions from landfilling raw, organic waste, are based in Manfredi et al. (2009) for landfilling in proper sanitary landfills.

$$\%\ of\ AVlfW = 1 - \frac{\sum_{t}^{T} lfW_t + \sum_{t}^{T} nprW_t + \sum_{t}^{T} npmW_t}{\sum_{t}^{T}\sum_{m}^{M}(mW_{m,t} + rW_{m,t}) + \sum_{t}^{T}\sum_{n}^{N} dsW_{n,t}} \times 100 \tag{60}$$

Data used for the computer model is presented in Appendix C. Table C1 contains the geographic positions and population data of municipalities; euclidean distance was used. Table C2 contains information on the degraded sites: type, area, status, the initial waste inventory of the degraded sites that will be mined, and geographical position. Table C3 contains data for opening and operating the facilities, according to their types. Table C6 contains the waste processing parameters, like processing cost, conversion rates, selling prices, GHG avoided, as well as the sources from where the values were taken. Tables C5 and C7 contains data for the existing RSCs and SLFs. Table C8 contains the data for the destination of ashes. Last, Table C4 contains all the data for the regeneration of the degraded sites, including revenues and avoided/captured GHG, according to the strategy defined for each site.

4.3 RESULTS AND DISCUSSION

Results for the objective functions, for the 16 combinations - four scenarios per region, two strategies per scenario - are illustrated in Figure 43: it contains the results for profit and net GHG savings achieved through maximisation of profit (MP), and for profit and net GHG savings achieved through maximisation of net GHG savings (MN).

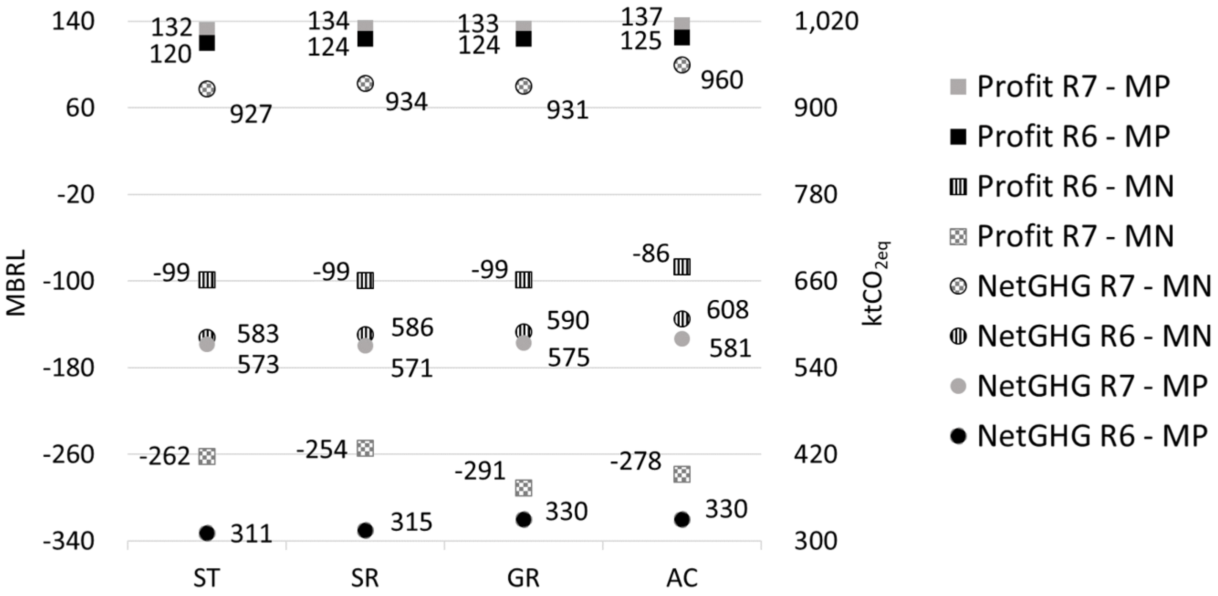


Figure 43: Profit, in millions of BRL, and net GHG savings, in kilotonnes of CO_{2eq}, for all 16 scenarios, for strategies of maximisation of profit (MP), and maximisation of net GHG savings (MN).

In the profit maximisation strategy, profitable solutions of over a hundred million Brazilian Reais (BRL) were achieved for both regions, in all four scenarios. A similar profit ranking can be observed: the highest profit was achieved in scenario AC - an expected result due to the increased waste volumes collected, and consequently processed. Scenarios SR and GR show roughly the same performance, varying less than 0.5% in Region 7. The smallest profit was achieved in scenario ST: 132.2 and 120.4 million BRL for regions 7 and 6 respectively; again, an expected outcome, since the smallest waste volumes are observed in this scenario. For the net GHG, the best performance was achieved in Scenario AC, region 7: 581 ktCO$_{2eq}$, followed by scenarios GR, ST and last, SR, with 571 ktCO$_{2eq}$. For region 6, net GHG savings increase from scenario ST until GR, dropping by a negligible amount for scenario AC. It can be seen in both regions an increasing profit trend, while net GHG savings remains in a similar level, but also showing growth. It can be concluded that, if economic and environmental performance are coupled, they progress together, instead of what is normally seen: an economic growth implying in a worsening of environmental performance.

The strategy of net GHG savings maximisation produced twice as much as the savings achieved in the strategy of profit maximisation, however with economic losses of over 85 million BRL. For region 6, the best performance in net GHG savings was achieved in Scenario AC, 608 ktCO$_{2eq}$, which also featured the smallest economic loss, -86.3 million BRL; no solution reached profit. From scenario ST until AC, an improvement of around 4% can be observed in net GHG savings, which is expected, since the more waste processed, the more GHG is saved. Economic losses remain roughly stable from scenario ST to GR, decreasing for scenario AC. For region 7, a similar improvement of around 4% is also observed in net GHG savings - from 927 to 960 ktCO$_{2eq}$. However, differently from region 6, in region 7, it is followed by an increase of 6% of economic losses: from -262 in scenario ST to -278 in scenario AC. From scenario SR to GR, there is an abrupt increase of losses, followed by a slight drop in the net GHG performance. For scenario AC, both metrics improve. Again, decoupling between economic and environmental performance is evidenced by the fact that the best performing scenario in net GHG for region 6, AC, also features the best economic performance.

Waste processing percentages, network topology, optimality gaps and Endurability are reported in Table 17, grouped by Region, scenario and maximisation strategy. A solution is considered the more optimal, the smaller is the optimality gap. Results are also compared with the targets defined in the state plan, PERS. Since the model can choose not to process all the waste collected, in the profit maximisation strategies, the percentage of recycled waste processed ranged from 91% in scenario SR, region 6, until 99.8% in scenario GR, region 6. The mixed waste processed ranged from 91.3%, scenario AC, region 7, to 99.8% in scenario SR, region 6. Highest percentage of processed waste for both types can be seen in region 6, scenario GR: 99.8% and 98.4% of recycled and mixed waste processed, respectively. In region 7, scenario ST shows the highest percentages, 99.8% and 95.7%. In the net GHG maximisation strategy, for all scenarios and regions, the model processes 100% of the waste generated.

The highest number of opened facilities in region 6 (12) was in scenario GR, yielding also the highest facilities balance, 11. These results are coherent with the increased waste percentages managed in Scenario GR. Scenarios ST and SR feature the same quantity of opened facilities, 11, consisting of three RSCs, seven bAeCCs - facility type preferred by the model to process mixed waste in the profit maximisation strategy - and one GP. In scenario SR, one bAeCC is closed. For scenarios GR and AC, one more RSC is opened; in scenario GR, seven bAeCCs are opened and one is closed, while in scenario AC, six bAeCC are opened and one is closed. No landfills are opened in this region by any solution.

The solution achieved for scenario ST, region 7, opens 17 facilities and closes 1, the highest among solutions in the profit maximisation strategy, with a balance of 16 - more opened facilities than scenario AC. Still in scenario ST, the model opens ten bAeCCs, distinguishing it from the other three solutions, which open one less, nine. The lowest quantity of opened (16) and closed facilities (0) was achieved in scenario GR. The difference between the solution achieved for scenario GR in comparison with AC is that the former opens a SLF in year 2026 and leave it open until 2038, while in the latter, a SLF is opened in 2018 and closed in 2024. Scenarios with the lowest facilities balance are SR and AC, with 15. In all scenarios, four RSCs and two GPs remain, while in scenario GR, one landfill remains opened.

Differently from profit, in the strategy of net GHG maximisation, the model opens only AnDPs for processing mixed waste. For region 6, all solutions opens and operates the same quantity of facilities, regardless of the waste generation scenario: four RSCs, two AnDPs, and one GP - again, no landfill is opened. For region 7, the quantities of opened and closed facilities vary, respectively, from 14 and 6 (scenario SR), 16 and 7 (scenarios ST and AC), and 17 and 8 for scenario GR. The facilities balance varies between eight (scenario SR) and nine (scenarios ST, GR and AC). In scenarios ST and SR, four RSCs are opened, and five in GR and AC. In scenarios ST, GR and AC, two AnDPs are opened, while in scenario SR, four. In all scenarios in region 7, two GPs are opened, while scenario ST is the only scenario in which an SLF is opened.

Metric	**Region 6**				**Region 7**			
	ST	**SR**	**GR**	**AC**	**ST**	**SR**	**GR**	**AC**
Profit maximisation								
% of waste processed:								
Recycled	91.6%	91.0%	99.8%	95.1%	99.8%	98.3%	95.5%	96.7%
Mixed	98.5%	99.8%	98.4%	95.7%	95.7%	95.2%	91.8%	91.3%
Facilities:								
Opened(Closed)	11(0)	11(1)	12(1)	11(1)	17(1)	16(1)	16(0)	16(1)
Balance[1]	11(3,7,1,0)	10(3,6,1,0)	11(4,6,1,0)	10(4,5,1,0)	16(4,10,2,0)	15(4,9,2,0)	16(4,9,2,1)	15(4,9,2,0)
Optimality gap	7.46%	4.88%	4.93%	7.23%	16.0%	15.7%	16.8%	17.9%
Endurability[2]	0.51709	0.51805	0.51703	0.51823	0.51257	0.51886	0.51450	0.51181
net GHG maximisation								
% of waste processed:								
Recycled	100%	100%	100%	100%	100%	100%	100%	100%
Mixed	100%	100%	100%	100%	100%	100%	100%	100%
Facilities:								
Opened(Closed)	7(0)	7(0)	7(0)	7(0)	16(7)	14(6)	17(8)	16(7)
Balance[3]	7(4,2,1,0)	7(4,2,1,0)	7(4,2,1,0)	7(4,2,1,0)	9(4,2,2,1)	8(4,4,2,0)	9(5,2,2,0)	9(5,2,2,0)
Optimality gap	0.76%	0.79%	0.70%	0.68%	5.7%	4.5%	5.4%	5.1%
Endurability[1]	0.52687	0.51969	0.52732	0.52696	0.52654	0.52597	0.52700	0.52636

[1] Facility types: Total(RSC, bAeCC, GP, SLF); [2] Average of 21 periods; [3] Facility types: Total(RSC, AnDP, GP, SLF).

Table 17: Network features for regions 6 and 7, for net GHG and profit maximisation strategies.

Optimality gaps observed for the solutions achieved through the profit maximisation strategy were higher than those observed in solutions achieved through net GHG maximisation: for region 6, profit maximisation, the greatest gap is observed in scenario ST (7.46%), while the smallest is observed in scenario SR, 4.88%. In the net GHG maximisation strategy, gaps are the smallest observed, all under the 1% margin, which can be considered near-optimal, as in Barahona e Chudak (2005); results for metrics are more consistent across the four scenarios, showing less variation. Optimality gaps achieved for region 7 where greater than those found in region 6, due to the increased size of the problem. For the strategy of profit maximisation, they ranged between 15.7% (scenario SR) and 17.9% in scenario AC. For the net GHG maximisation strategy, they ranged between 4.5% (again in scenario SR) and 5.7%, in scenario ST - around three times smaller optimality gaps, in comparison with the profit strategy.

Concerning the solution's Endurability, overall results achieved can be considered satisfactory, reflecting the adoption of resilience principles during the conceptual design of the supply network. Differences among solutions can be imputed to the different quantities of facilities: the greater the quantity, the smaller is the Endurability average. The overhead increases with the number of facilities, which decreases the Endurability, making the system more interconnected. Lowest Endurability average is found in profit maximisation, region 7, scenario AC (0.51181), while the highest value is observed in net GHG maximisation, region 6, scenario GR, 0.52732. From the ENA results, one can conclude that, with around seven facilities, the system features a balanced resilience.

Results for regions 6 and 7 are aggregated in Table 18, for the whole region of Norte Pioneiro. Metrics related with the objective functions are reported again (profit from profit maximisation and net GHG savings from net GHG maximisation), together with capital expenditures (from profit maximisation) and capital GHG emissions, from net GHG maximisation. Other metrics reported for both strategies are: percentage of avoided landfill waste, jobs balance, avoided GHG emissions from landfilling raw, organic waste and last, revenues from auctioning carbon credits, as another potential source of income.

For the profit maximisation strategy, scenario AC shows the highest profit, followed by scenarios SR, GR and ST. The biggest investment was performed in Scenario GR - which explains why it shows a lower profit than SR -, followed by scenarios AC, and SR tied with ST for the lowest CAPEX. A similar ranking is found in the net GHG maximisation strategy, but with scenario GR showing a slightly greater net GHG savings than scenario SR, also explained by the difference in the capital GHG emissions - the greatest among the four scenarios. The CAGEM ranking is, first scenario SR, followed by AC, GR and last, ST.

Metric	Norte Pioneiro			
	ST	SR	GR	AC
Profit maximisation				
Profit[1]	252,514	257,625	257,543	262,262
CAPEX[1]	192,438	192,438	192,947	192,481
Avoided waste lf.[2]	94.40%	94.34%	92.90%	91.97%
Jobs[3]	1,003	993	1,114	1,100
Raw waste GAV[4]	279.17	338.11	336.40	292.33
Carbon Credits REV[5]	13,568.83	14,286.57	14,479.07	14,032.98
net GHG maximisation				
net GHG[6]	1,509.84	1,520.11	1,520.33	1,568.86
CAGEM[6]	145.61	161.99	154.26	157.77
Avoided waste lf.[2]	97.18%	97.19%	97.14%	97.04%
Jobs[3]	1,024	1,020	1,137	1,137
Raw waste GAV[4]	356.68	358.99	360.79	371.76
Carbon Credits REV[5]	21,777.61	21,917.84	21,941.46	22,635.37

[1] in kBRL; [2] Percentage of avoided waste landfill;

[3] Created minus terminated job positions;

[4] Avoided GHG emissions from organic raw waste landfill, in $ktCO_{2eq}$;

[5] Potential revenues from carbon credits auctioning, considering € 2.70 per tCO_2 - source: Bovespa (2018) - and € 1.00 = BRL 4.32, source: Reuters (2018); [6] in $ktCO_{2eq}$.

Table 18: Aggregated results for the region of Norte Pioneiro.

More than ninety per cent of the waste generated is diverted from landfills in the worst case, which shows the eco-effectiveness of the solutions achieved. In the best case, 97.2% of reduction is achieved in Scenario SR. Compared with the current landfilled waste percentage of around 83%, a massive reduction in waste landfilled is achieved, overcoming by far the target defined in the state plan PERS - 30% reduction of landfilled waste in the long-term (Envex; Engebio, 2018a). Considering the reality of the region, the amount of GHG avoided is even larger, due to the improper landfilling currently performed in controlled landfills and dumping grounds. In terms of jobs balance - an indicator for the social dimension of sustainability -, both strategies shows roughly similar results, despite the difference in the overall quantity of opened facilities. Scenario SR in profit maximisation strategy is the only scenario under one thousand jobs: 993. All other scenarios showed a jobs balance of over one thousand, with scenarios GR and AC in the net GHG maximisation strategy with the highest jobs balance: 1,137.

Carbon credits are another possible source of revenue, achieved in auctions promoted by stock market management institutions (BOVESPA in Brazil), for certified GHG reductions. In this research, they were calculated from the sum of net GHG savings performances with the avoided GHG emissions from raw organic waste landfilling. Values range from 279.17 $ktCO_{2eq}$ (for scenario ST, profit maximisation) to 371.76 $ktCO_{2eq}$ - scenario AC, net GHG

Year	Strategy	
	profit	net GHG
2018	0	0
2019-2028	7	23
2029-2038	23	23

Table 19: Quantity of regenerated sites per strategy, per year.

maximisation. This behaviour is expected, since the lowest avoidance is achieved in the lowest waste generation scenario, less focused on environmental performance. The highest avoidance is achieved in scenarios with largest waste generation volumes, in the strategy of maximising net GHG savings. The lowest revenue achieved is in scenario ST of profit maximisation, and the highest revenue achieved in scenario AC of net GHG maximisation. This revenue can be added to the economic performance of each solution, making up to 276 million BRL of total profit in scenario AC, profit maximisation.

The modelling logic of the compulsory regeneration of degraded sites has led to simplistic outcomes: in the profit maximisation strategy, regenerated sites which become solar farms (in total, seven) are regenerated right in the first possible period, 2019. The remaining sixteen sites, for which the reforestation and transformation into parks strategies were defined, were only recovered in the last period allowed, 2029. This is summarised in Table 19, showing the quantity of regenerated sites per year, for each maximisation strategy. Results are in compliance with the target established in MMA (2012) for the year 2031, assuming that the degraded 23 areas correspond to 100% of the degraded areas in the region.

In Figure 44, the distribution of facilities across the region of Norte Pioneiro can be observed. (a) is the distribution of facilities achieved through profit maximisation, while (b) is the distribution achieved through net GHG maximisation. In both cases, facilities are concentrated in the high latitudes of the whole region; it is possible to conclude that it is more interesting for the southern municipalities to transport their waste to the northern municipalities than opening local facilities. Allowing the possibility of opening smaller sorting cooperatives and smaller composting units to the model could possibly change this outcome, although in the case of the smaller composting centres, this was not evidenced. The greater number of closed facilities in region 7 is also highlighted by the facilities filled with a grid pattern.

The dynamic behaviour of the waste network can also be analysed from the model outputs. The box-plot graph in Figure 45 illustrates the evolution of profit in Region 6, considering results of the four scenarios in each year in the 21-year period, in the profit maximisation strategy. As it is normally expected, losses are observed in the first periods due to large investments needed for opening waste processing facilities; these losses are over 15

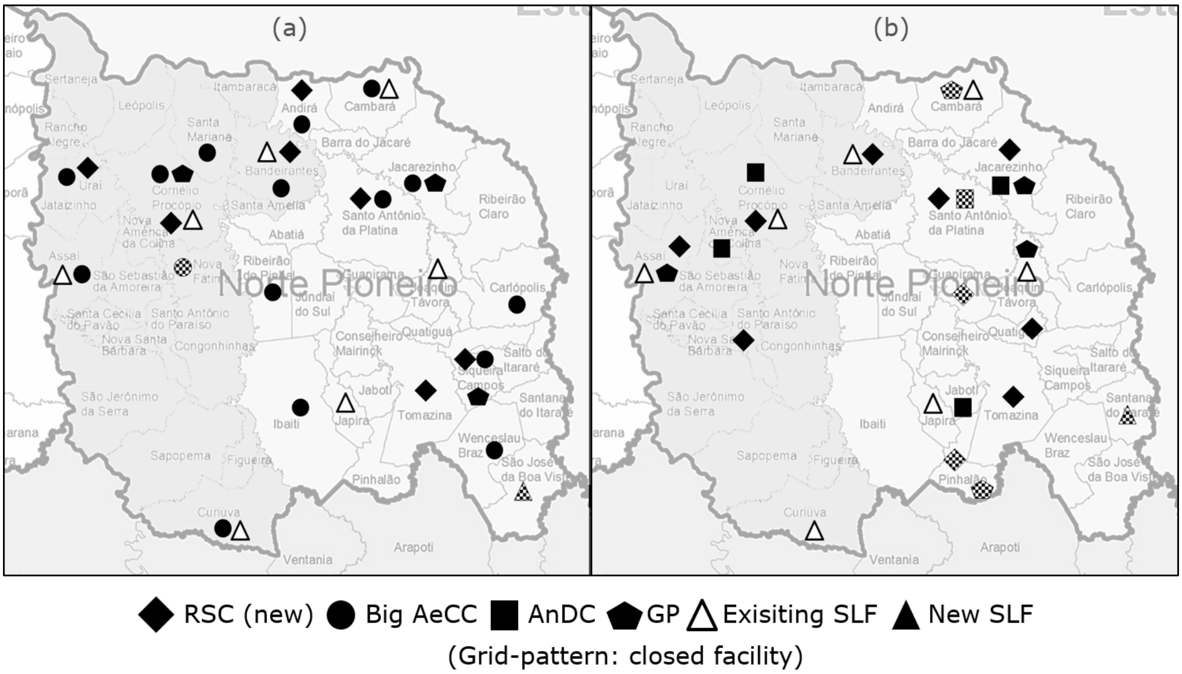


Figure 44: Location of facilities across the region of Norte Pioneiro, scenario SR. (a) is the solution achieved through profit maximisation, and (b), the solution achieved through net GHG maximisation.

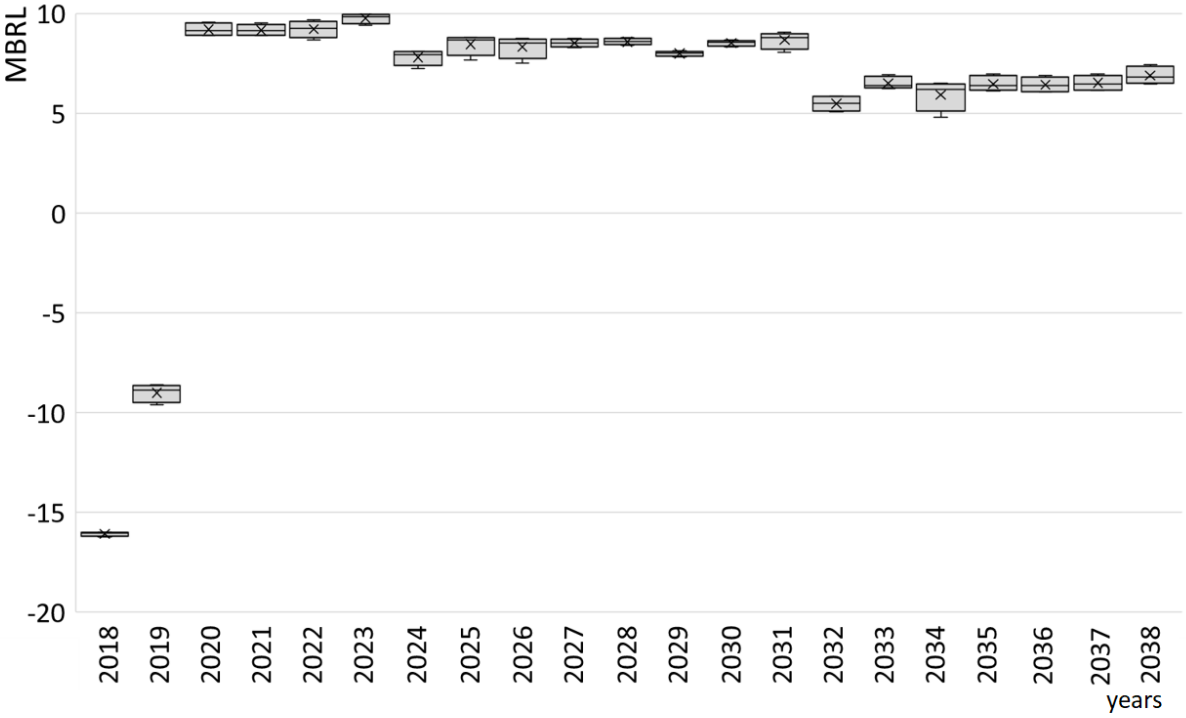


Figure 45: Profit performance of Region 6 through time - profit maximisation.

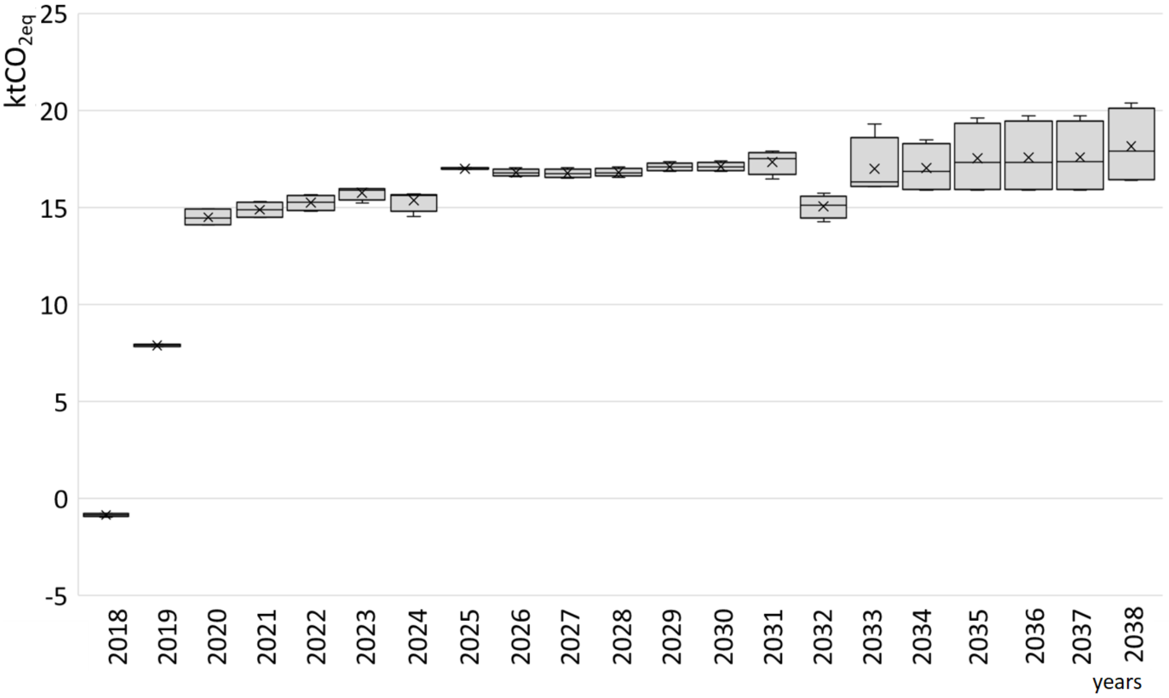


Figure 46: net GHG savings of Region 6 through time - net GHG maximisation.

million BRL in 2018 and roughly 10 million in 2019. From 2020 onwards, profits of around 10 million BRL per year can be observed in all four scenarios, decreasing abruptly in 2024 and 2032 where there are the waste volume peaks, increasing again afterwards. Figure 46 is the box-plot for the net GHG savings considering all four scenarios in the net GHG maximisation strategy. In this case, a negative net GHG performance is observed only in the first period, 2018; from 2019 onwards, positive net GHG savings are observed, progressing as in the profit maximisation strategy. net GHG savings range around 15 ktCO$_{2eq}$, increasing with time, while the dispersion of values increase as well, following the different waste volumes generated in each of the four scenarios.

In Figure 47, the decisions for opening and closing facilities performed by the model can be observed, for the 21-year period, for region 7, scenario GR, net GHG savings maximisation. Four types of opened/closed facilities are plotted: anaerobic digestion plants (AnDP), gasification plants (GP), recycling sorting centres (RSC) and sanitary landfills (SLF). The network starts the period with three AnDPs, two GPs, one SLF and one RSC. The quantity of RSCs is increased to seven in 2024, oscillating between 7 and 6 until 2037, where five RSCs remain opened. The number of AnDPs decrease from three to two in 2033; the number of GPs increases to three in 2021 and reduces again to two near the end of the period. Finally, the only SLF opened in 2018 is closed in 2034.

Through these dynamics, the model shows its flexibility and adaptability, modifying

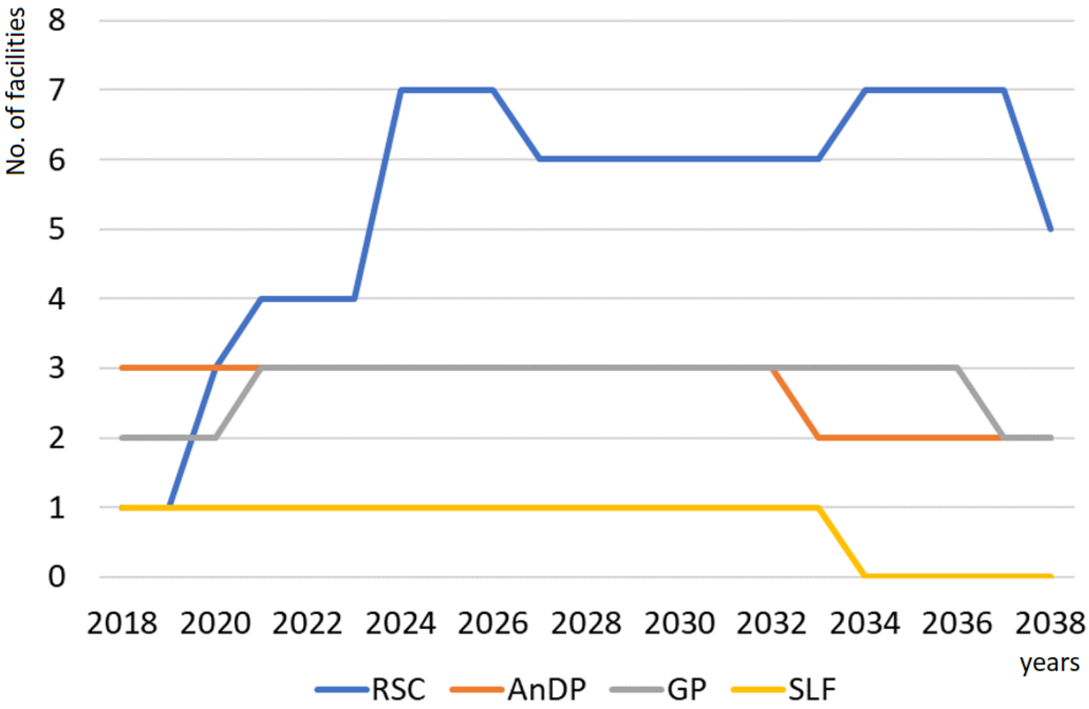


Figure 47: Opening and Closing Facilities through time at Region 7, Scenario GR, net GHG maximisation.

inputs, outputs and operations if and when needed. A further look into the dynamics of opening and closing facilities reveals that the model changes the locations of a facility, closing it in one municipality and reopening it in a different municipality. This suggests that facilities could be designed and manufactured for mobility, which could reduce the cost from closing and opening new facilities. Job positions are also created and terminated following the opening and closing of facilities, according to the number of job positions required for each facility type, defined in Table C3. This information could be used for managing these changes along with the local community, anticipating social effects from labour requirements and resignations.

Figure 48 shows the variation in Endurability for Region R6, scenario SR, for both strategies profit maximisation and net GHG maximisation, for every year in the 21-year period. In the profit maximisation, the network achieves the highest redundancy in year 2032, outside the window of vitality. In the strategy of net GHG maximisation, results of Rel.ASC for the year 2023 show a high organisation level: if it happens to be a turbulent year, the network may struggle; if its a stable year, it may perform more efficiently, bringing enhanced results. In Brazil, general elections are scheduled for the end of 2022; therefore, 2023 is likely to feature turbulence. Differently from Souza et al. (2019), the strategy focused on environmental performance did not harm the ENA results. In fact, the opposite is observed: overall, solutions achieved through the net GHG strategy showed the best results in Relative Ascendency and Endurability, due to the balance achieved between Overhead and Ascendency from the smaller

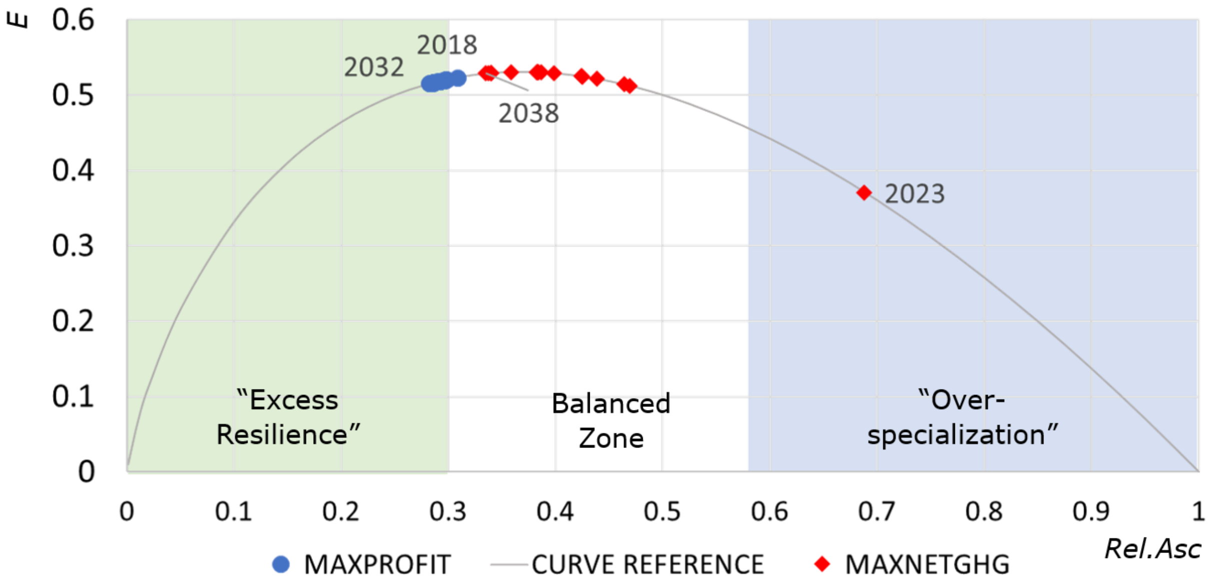


Figure 48: Endurability variation for Region 6, Scenario SR, for both optimisation strategies.

quantity of opened facilities.

In Appendices D and E, Sankey diagrams can be found for region 6, scenario SR, profit maximisation and net GHG maximisation, respectively. The diagrams stress the difference on the quantities of processed waste and the mass flows through the waste network. Electricity generation is also represented, without scale. The diagrams detail the input flows for each waste type, the waste processing types chosen in each maximisation strategy, and the outputs types achieved, with respective quantities.

Finally, Figure 49 shows the Pareto frontier for Region 6, scenario SR, illustrating the trade-off between maximisation strategies, were the x-axis representing the net GHG performance in $ktCO_{2eq}$, and the y-axis representing the profit performance, in MBRL. The Pareto solutions are plotted with respective coordinates, in the format "net GHG, profit". The two extreme performances come from *maxPROFIT* (a short for strategy of profit maximisation), point (315, 124) and *maxnet GHG* (a short for strategy of net GHG maximisation), point (586, -99). Three intermediate solutions are plotted: (328, 121), the result for the weighting distribution "OEM"; (500, 11), result of weight distribution "balanced", and (579, -87), the result from the weight distribution "green company". It is possible to reach up to around 500 $ktCO_{2eq}$ and still achieve economic profit.

A summary of metrics for the five solutions in the Pareto frontier is reported in Table 20. "Green" is a short for "Green Company", with a weight of 70% to the net GHG objective and a weight of 30% to the profit objective. Only solutions Green and maxnG process all the waste generated; Balanced process all the recyclables, and do not process 2.5% of the mixed

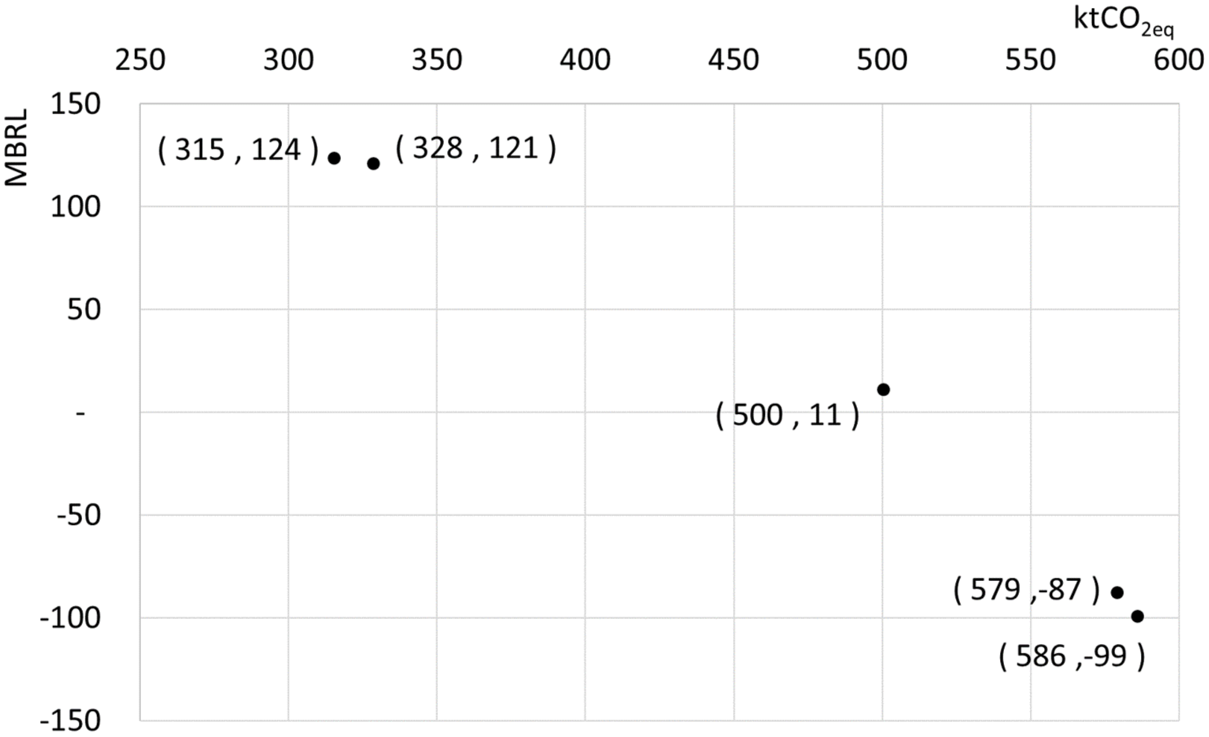


Figure 49: Pareto frontier of non-dominated solutions for Region 6, scenario SR.

Metric	Region 6, scenario SR				
	maxProfit	“OEM"	“Balanced"	“Green"	maxnG*
% of waste processed:					
Recycled	91.0%	99.9%	100%	100%	100%
Mixed	99.8%	99%	97.5%	100%	100%
CAPEX[1]	-47,493	-47,536	-99,506	-152,529	-150,466
CAGEM[2]	-24.081	-25.839	-31.816	-39.200	-38.496
Facilities:					
Opened(Closed)	11(0)	12(0)	9(1)	8(1)	7(0)
Balance[3]	11(3,7,0,1)	12(4,7,0,1)	8(4,2,1,1)	7(4,1,1,1)	7(4,0,2,1)
Rel.ASC	0.2882	0.2842	0.3732	0.3918	0.3993
Endurability	0.51709	0.51524	0.52906	0.52723	0.51969
Optimality gap	4.88%	optimal	8.25%	11.0%	0.79%

* maxnG is a short for “maximisation of net GHG";

[1] in kBRL; [2] in ktCO$_{2eq}$; [3] Facility types: Total(RSC, bAeCC, AnDP, GP).

Table 20: Summary of solutions in the Pareto frontier.

waste. OEM falls short of processing all the waste. CAPEX suffers an abrupt increase in the Balanced solution, due to the opening of an AnDP. Both CAPEX and CAGEM reach the highest value in solution Green Company. The number of opened facilities increases from 11 to 12 until solution OEM; decreasing to 9 in solution Balanced, to 8 in the Green Company, and to 7 at solution *maxnG*. Solutions Balanced and Green close one facility - a bAeCC in the Balanced, and an AnDP in solution Green Company.

Solution maxProfit opens three RSCs, while all other solutions open four. Solutions maxProfit and OEM open only bAeCCs, while solutions Balanced and Green Company open both bAeCCs and AnDPs. Solution maxnG opens two AnDP and no bAeCC. All solutions open one GP. The quantity of operating facilities varies accordingly. Rel.ASC progressively increases from maxProfit towards maxnG, while Endurability reaches the highest level in the Balanced solution, featuring the highest possible performance in the ENA model. Last, optimality gaps ranged from 11 per cent in solution Green Company, while in solution OEM, an optimal value was achieved.

4.4 CONCLUSIONS

In this Chapter, the Regenerative Supply Network design procedure was used for the design of a resilient, sustainable, regenerative waste management network for the region of Norte Pioneiro. A purpose linked with the network function was identified after analysing the region as an SES. Land use was identified as an environmental problem in which the network could contribute. A redesign of the waste management system is required, since it currently landfills more than 95% of the waste disposed by households. Additionally, 23 sites degraded by improper waste disposal were identified in the region. As these sites are linked with the network function, the waste network should engage on their regeneration. Outputs were redesigned; a waste management network was conceptualised and its performance optimised. Regeneration strategies were defined, following the needs of the surroundings of each site. The optimisation model outputted network configurations that maximise profit or net GHG savings, for both regions 6 and 7.

The RSND procedure successfully supported the design of a regenerative waste network. Even through the profit maximisation strategy, a considerable quantity of avoided GHG was achieved, due to the eco-effective approach used in the early design stages. Second, results achieved showed a relative homogeneity; through comparing solutions for each scenario, it was possible to understand the impact of changes in waste volumes in the waste network topology and performance. The optimisation model could provide solutions regardless of the changes in waste volumes. The waste management network fulfilled both its purpose and function: while it managed waste flows collected yearly in the municipalities, it also engaged in the task of mining the waste from degraded sites, and transformed all the 23 sites into solar farms, producing electricity, reforested areas or recreational parks, enhancing the green covering of region NP, improving the region's resilience. The optimisation stage was essential to assure economic sustainability to the network, which currently faces annual losses with waste management - in 2017, the Norte Pioneiro region faced losses of 18.6 million BRL (Brasil, 2016). After optimised for profit, all scenarios achieved profit levels at least five times greater than these losses - which is a major contribution from this research for the Brazilian context: the importance of using scientific methods to support decision-making in governmental administration. The anaerobic digestion plant model was unable to achieve economic sustainability, failing as an option in the *maxProfit* scenario. Since it is among the most interesting option to be chosen in an integrated waste management network, its economical feasibility should be improved with policies directed to biogas production. Careful must be taken while looking to these figures, due to the considerable optimality gaps observed for the majority of scenarios.

The transdisciplinary characteristic of the design process is evident from the different skills and disciplines involved in the waste network design: it is possible to observe disciplines like geography, engineering, chemistry; different modelling techniques were also employed, like SD, optimisation and flowcharts. The results of this research can be used by the other eighteen regions in the state of Paraná as a benchmark, since they share common characteristics, like population size.

Strategies of food reuse were not selected due to the degradation stage of the MSW: it could be selected if food was redirected straight to reuse right after it was disposed, impacting the number of facilities opened to process organic waste, as the social performance of the system would improve. Strategies for reducing waste generation and increasing waste collection could be implemented progressively, year by year, and not in steps like it was performed, decreasing the amplitude of oscillations in waste collection volumes, which could affect the optimality gaps observed in solutions achieved. The waste hierarchy could also be modelled within the optimisation model, setting weights for each strategy according to its environmental performance, leading to different trade-offs with the economic performance.

Splitting the model into two the two micro regions R6 and R7, to achieve integer solutions in a feasible time, reduced the system's optimality. This can be evidenced comparing, e.g., for scenario ST, the upper bound for the entire region (2.9 MBRL) and the sum of the upper bounds for regions 6 and 7 (2.84 MBRL) - a loss of 2%. Near-optimal solutions were only achieved through the strategy of net GHG maximisation, for Region 6; the only optimal solution was achieved in the Pareto solution for the weight distribution “OEM". Further research can be conducted in both directions: improving the optimality gaps of those solutions, and solving the problem for the whole region, which will require improved heuristics. Optimising only the area around the borders between regions 6 and 7 could be a direction, fixing the positions and facility types a certain distance away from the border.

The Ecosystem Network Analysis was used as a metric for network resilience, reporting results coherent with the adoption of resilience principles during the conceptual design of the network. An analysis of the evolution of the ENA results through time was also performed; from the author’s knowledge, this has never been attempted before. Further research could strengthen the use of ENA as a metric for resilience, using indicators to monitor the effectiveness of the regeneration activities, like the LIFE (Lasting initiative for Earth) certification methodology (REALE et al., 2019), improving the quality of the data used quantify performance, e.g., prices, costs, GHG emissions, and data concerning inputs, outputs, waste processing and construction of facilities, achieving more realistic, context-related and reliable results. Despite all the limitations, the model provides decision makers with valuable information on the behaviour of an adaptive waste management network which processes a variable volume of waste collected through the 21-year period, while simultaneously regenerates 23 degraded sites.

5 SYNTHESIS

In the previous chapters, artefacts were designed within the Operations Management functions of product/service development, production and delivery, with the objective of regenerating the environment. An investigation was performed in the network and system levels, supporting the transition from anthropocentrism towards ecocentrism - the aim of this thesis. In this Chapter, outcomes are compared for insights and conclusions. Limitations of this thesis, as well as originality, contributions and implications are also discussed.

In Table 21 the objectives defined in chapter one and the outcomes achieved in each chapter are compared. In chapter two, the areas advancing sustainable design in operations management were identified, as well as the state of the art in each area, and future research directions. Among the main trends observed, two were explored in the following chapters: sustainable supply chain design and integrated waste management. A major reflection from chapter two was that a systemic approach to perform SD in OM implies in dealing with multiple disciplines, which demands a methodology to bridge concepts into a common framework: transdisciplinarity research. TR's problem-focused approach and the search for the common good also fitted with the research's aim of contributing with the environmental regeneration, setting the basis for the development of the research.

In chapter three, the trend of sustainable supply chain design was explored for the creation of an artefact that supports regenerative design and development in the long term, combining multiple disciplines through Transdisciplinary Approach. The ecocentric view, together with a systemic approach, implied on the evolution of *sustainable supply chain design* into *regenerative supply networks design*. The long term perspective was addressed using resilience principles during the conceptual phase of the design, verified quantitatively with Ecosystem Network Analysis. The approaches of eco-effectiveness and eco-efficiency were combined, resulting on a “doing the right things right for the environment" approach; eco-efficiency cannot be left behind since many technological solutions still impacts the environment. The regenerative supply network, the design process definition and the procedure were developed using DSRM, and the artefact designed - the Regenerative Supply Networks

Chapter	Objective(s)	Outcomes
Two	Identify subject areas and categories, main authors, most relevant papers and the state of the art of Sustainable Design in the context of Operations Management.	• Mindmap connecting areas and research categories evolving Sustainable Design in Operations Management; • Systemic analysis providing insights about the state of the art, research trends and future research directions.
Three	Propose a definition and a procedure for the design process of regenerative supply networks.	• The regenerative supply network design process is defined, merging multiple concepts; • Based in Transdisciplinary Research, a design procedure consisting of four steps is proposed.
Four	Demonstrate and evaluate the implementation of the Regenerative Supply Networks Design Procedure for the design of a waste management network that regenerates degraded sites.	• Adaptive waste management network which diverts waste from landfills and simultaneously recovers degraded sites; • Network configurations, with respective optimal performances in economic and environmental dimensions, reporting of social performance and Pareto frontier analysis.

Table 21: Review of Objectives and Outcomes for each Chapter.

Design procedure - is demonstrated and evaluated in chapter four.

The research stream of integrated waste management is explored for the demonstration and evaluation of the RSND procedure, in chapter four. Multiple disciplines were used in the depiction of the SES - the region of Norte Pioneiro, Paraná -, the “client” of the waste management network - the STS being designed. This depiction revealed that land use is a one major factor affecting the resilience of the ecosystems in Norte Pioneiro. Besides, in the current system, the majority of the waste collected is landfilled, contributing to land use through improper waste disposal - a major problem being caused by the STS to the SES. Therefore, the purpose defined for the network was to regenerate sites degraded by improper waste disposal.

The interaction dynamics between the SES and the waste management network (the interacting STS) were modelled in a Stocks and Flows diagram. Variables influencing the generation or the reduction of waste were modelled, outputting waste production volumes for a 21-year period, for the region of Norte Pioneiro. These outputs were used as inputs in a multi-period (21 years), multi-scenario (four population growth scenarios were considered: stagnation, slow recovery, growth resumption and acceleration), multi-objective (environmental and economic objectives, net GHG savings and profit, respectively) optimisation model. This structure ensured that the supply network being designed was *adaptive*, i. e., was capable to adapt to changes in the environment. The introduction of the dimension of time addressed the "long-term" aspect of the regenerative supply network definition from chapter three.

The artefact "RSND procedure" was evaluated through an analysis of the waste network performance, in terms of (i) how it fulfilled both its purpose and function, and (ii) on its sustainable performance in the economic (profit), environmental (net GHG savings) and social (creation of job positions) dimensions. The purpose of environmental regeneration was achieved: 23 degraded sites were recovered in one of the three strategies defined: reforested areas, recreational parks or solar farms. Its function was also delivered: the waste collected from the municipalities was processed and recovered by the waste management network. The waste management network presented satisfactory performances in the three sustainability dimensions when the profit maximisation strategy was used, achieving reasonable profit, net GHG savings, and creating jobs. It is possible to conclude that the RSND procedure has driven the design of a supply network that regenerates the environment, therefore achieving its objective.

The last activity in DSRM, Communication, was performed through multiple instances, including conferences, journal papers and finally, this thesis. All the instances of communication performed during this research are listed in the bullets below, in chronological order:

- de Souza, V., & Borsato, M. (2015). Sustainable Consumption and Ecodesign : a Review. In Transdisciplinary Lifecycle Analysis of Systems: Proceedings of the 22nd ISPE International Conference on Concurrent Engineering, at Delft, Holland (Vol. 2, pp. 492–499);
- de Souza, V., & Borsato, M. (2016). Sustainable Design and its interfaces: an overview. International Journal of Agile Systems Management, 9(3), 183–211;
- de Souza, V., Borsato, M., & Bloemhof, J. (2016). Designing eco-effective reverse logistics networks. In M. Borsato, N. Wognum, M. Peruzzini, & J. Stjepandic (Eds.), Advances in Transdisciplinary Engineering (Vol. 4, pp. 851–860). Curitiba: IOS Press;

- de Souza, V. (2016). Design of upcycling-optimized reverse logistics networks. *PhD. Qualifying proposal defense*. Federal University of Technology - Parana. Curitiba, Brazil;
- de Souza, V., Borsato, M., & Bloemhof-Ruwaard, J. (2017). Designing Eco-Effective Reverse Logistics Networks. Journal of Industrial Integration and Management, 2(1), 1750003;
- de Souza, V., Bloemhof-Ruwaard, J. M., & Borsato, M. (2018). Evaluating the Resilience Performance of an Optimized Supply Chain Using Ecosystem Network Analysis. 5th International EurOMA Sustainable Operations and Supply Chains Forum, 1–12.
- de Souza, V., Bloemhof-Ruwaard, J. M., & Borsato, M. (2019). Towards Regenerative Supply Networks: a design framework proposal. *Journal of Cleaner Production*, 221, 145–156;
- de Souza, V., Bloemhof-Ruwaard, J. M., & Borsato, M. (in press). Exploring Ecosystem Network Analysis to balance resilience and performance during Sustainable Supply Chain Design. International Journal of Advanced Operations Management;
- de Souza, V., Bloemhof-Ruwaard, J. M., & Borsato, M. (in preparation). Designing a regenerative municipal solid waste management network for the region of Norte Pioneiro, Paraná.

The artefacts developed in this research are contextualised in a cascading representation in Figure 50, based in Bots e Daalen (2012). The waste management network is an artefact resulting from the implementation of the RSND procedure, the artefact designed using the DSRM, which is, in turn, an outcome from previous research: the DSRM structure of Peffers et al. (2007). The boundaries of this research are represented by the solid lines, and the dashed line only separates the different design levels. The operation process of the waste management network was left outside of the scope of this thesis. The RSND procedure artefact can be regarded as a social/psychological artefact, as it defines rules; i.e., which activities and requirements are needed to characterise a regenerative supply network. The waste management network can be regarded as both a social/psychological and a material/physical artefact, comprising of rules - agreements about where and when the waste should be transported -, and infrastructure - like plants, trucks and waste (BOTS; DAALEN, 2012). In the following section, thesis' implications are reviewed and discussed.

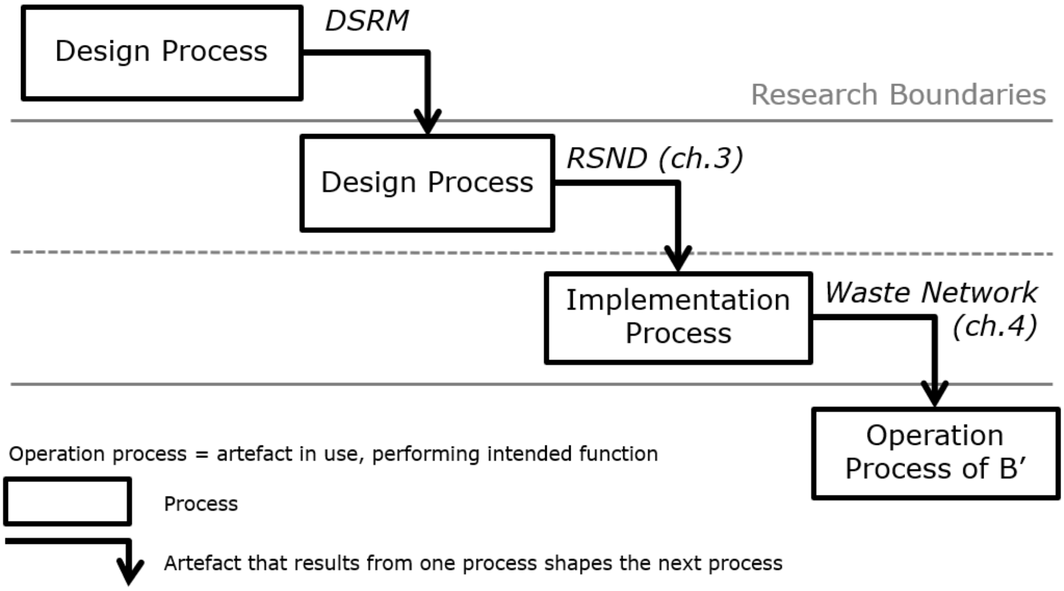


Figure 50: Synthesis of the Artefacts Designed. Based in Bots e Daalen (2012).

5.1 IMPLICATIONS

In this section, eight general implications are discussed, since in each chapter, specific implications were already addressed. Each implication is summarised in a quote, and discussed in the following paragraph(s).

> Both eco-efficient and eco-effective approaches are needed during the transition from anthropocentrism to ecocentrism.

Artificial systems have not reached a development status in which they are fully sustainable; ultimately, they will damage the environment in some way. Therefore, both approaches are needed: eco-effectiveness to design systems that “do the right things" for the environment, and eco-efficiency to minimise currently inevitable environmental impacts, “doing things right". Through the eco-effective approach, one can make sure that these impacts are reverted in the long-term. In this thesis, the business-oriented paradigm is inverted, transformed into a system-oriented paradigm: instead of designing systems to be profitable, decreasing their environmental impact, the system is designed to be regenerative first, increasing their economic performance afterwards. In doing so, the system is unlocked to progress towards regenerative development (LODDER et al., 2014).

Assuming eco-effectiveness as a first priority is in line with Raworth (2017), which states that the environmental dimension should be prioritised over societal and economic dimensions, as the latter two cannot exist without the first. Whatever is the perspective used, if any of the three dimensions is overlooked, it is very unlikely that ecocentric initiatives succeed. Eco-efficiency is needed to assure profit, as without it, sustainable initiatives are doomed to be replaced by a less environmentally-friendly initiative. Niero et al. (2017) also integrated both eco-efficient and eco-effective approaches. A different combination was performed between Life Cycle Assessment (an eco-efficiency inspired tool) and Cradle-to-cradle - eco-effective - in a stepwise procedure for the optimisation of closed-loop packaging systems, based in Circular Economy. In this thesis, a much more comprehensive procedure was achieved since it was grounded in transdisciplinarity, while the integration between eco-effectiveness and eco-efficiency resulted in a combination between regenerative design and the maximisation of profit and net GHG savings.

> Transdisciplinarity provides unconventional insights when investigating sustainability problems.

In this research, the eco-effective approach was first drawn from the principle of Upcycling, developed in the discipline of Architectural Design by McDonough e Braungart (2013). Sustainable Supply Chain Design was first approached from the perspective of Reverse Logistics (FLEISCHMANN, 2001) in the firm-level; then it was expanded to the inter-firm, network level, arriving in the concepts of Industrial Symbiosis (LOMBARDI; LAYBOURN, 2012) and Industrial Ecology (PECK, 1996), from Industrial Engineering. As in Bergendahl et al. (2018), searching for the most effective science to handle the problem at hand is one of the first activities, after the research scope was defined, performed in chapter three. From each discipline and concept, a contribution was extracted: from Upcycling, principles “optimise, optimise and optimise”, “gaze around before you begin”, “waste equals food” (also found in IS) and “speak through positives” were adopted. The waste management network was conceptually modelled based in IS techniques, depicting input and output flows. The “common good" - environmental regeneration -, is a concept from TR. From Supply Chain Design, optimisation techniques were used to assure economic sustainability.

> Supply networks can regenerate the environment with sustainable performance.

In chapter four, the RSND procedure guided the design of a waste management system that regenerated degraded sites. In the profit maximisation strategy, sustainable performance was achieved in both economic (profit) and environmental objectives (net GHG savings). Achieving economic sustainability is a major challenge, since multiple interests must be reconciled, and it was achieved considering non-traditional stakeholders (TONELLI et al., 2013) - e.g., neighbours of the degraded areas - and the increased costs from regeneration activities, which, in the case of reforested areas, do not result in revenues.

> Ecocentric-oriented systems must be designed following Resilience principles. If the system is optimised, Resilience should be checked afterwards, to ensure that optimisation did not lead to fragility. However, its emergent nature cannot be overlooked.

The inclusion of the resilience dimension enables sustainability gains in the long term. One can have an artefact that is both eco-effective and eco-efficient, but if it does not cope with eventual changes or disruptions, it is very likely that damage from its failure may be hard to revert. A system that replaces a less environmental-friendly system is not allowed to fail, under the risk of undermining the reputation of such initiatives, resulting on drawbacks that may take years, and energy, to overcome - such impacts are yet to be investigated. There are multiple ways to address resilience in a supply network: in this thesis, the approach of design for resilience was chosen (FIKSEL, 2016), based in the work of Pettit et al. (2013), differently from the approach used by Mari et al. (2014), where disruption probabilities were calculated for the regions where the supply network operates, or from Fahimnia e Jabbarzadeh (2016), which optimises different disruption scenarios, reaching an optimal performance in a compromise between stable scenarios and scenarios where one or more disruptive events take place.

In chapter three, resilience principles are considered during the system conceptualisation, and Ecosystem Network Analysis is used to quantify resilience, demonstrated in chapter four during the waste management network design. The ENA model is limited in the analysis of resilience due to its highly aggregated nature, covering but two dimensions of resilience: redundancy and interconnectedness. ENA results responded to the resilience principles addressed; regardless of the optimisation strategy used, results were inside the window of vitality, or just about entering it from the left side of the curve, meaning that systems were exceeding in overhead, rather than fragility. One must not overlook the fact that resilience is an emergent property (CHOPRA; KHANNA, 2014); subjected to uncertainty coming from the surroundings, the reason why models based in the maximum entropy principle like the ENA provide interesting insights (VENKATASUBRAMANIAN et al., 2006).

> Design frameworks define working principles, the “what”. “How” to design is defined by the designer, according to the context of application.

Design frameworks normally take one of the two directions: discussing concepts and defining design principles (BLIZZARD; KLOTZ, 2012; JOORE; BREZET, 2015; LODDER et al., 2014), or building a framework around a modelling paradigm (REBS et al., 2019). The *means* to deploy such principles are normally out of scope, leaving to the designer the responsibility to choose the techniques he/she is most comfortable with, or applying techniques suited to the construct being represented. The RSND procedure follows the first direction, since it does not specify which modelling paradigms to use. For the case of the waste network, System Dynamics and Optimisation modelling techniques were used, but Agent-based modelling could be used instead, producing an artefact of a diverse nature, providing different outcomes and insights. This is a main implication when creating artefacts in the context of OM: choosing the modelling paradigm begins with the identification of the flows being studied.

> The integration of the Socio-Ecological with the Socio-Technical views allows the understanding of interactions among artificial and natural systems.

Normally, both schools of though remain apart from each other; researchers that adopt the SES view consider technology as an exogenous factor (SMITH; STIRLING, 2010), focusing on ecosystems resilience, stewardship and safe operating spaces Folke et al. (2016), Rockström et al. (2017). Research on STS have progressed on multilevel analysis, regarding all systems as nested socio-technical systems (GEELS, 2012), employing technology to achieve drastic reductions on carbon emissions (SMITH; STIRLING, 2010). In this research, both views are used in the design of a waste management network (which fits in the description of an STS, design-oriented) for the region of the Norte Pioneiro (which fits in the description of an SES, resilience-oriented). The combination of the two views support the designer in the transition from analysis (of the surroundings, supported by SES) to synthesis (of a new STS) when dealing with multiple abstraction levels, as explored in Joore e Brezet (2015).

Ecocentrism is the path in which the SES and the STS views can be integrated, realising the view of Smith e Stirling (2010); both artificial and natural systems benefit from this integration, improving their resilience (MANG; REED, 2012). A similar proposition is formulated by Gruner e Power (2017), which define five socio-ecological “intergradation" principles - the “gradual merging of the social and ecological dimensions to result in a more harmonious interdependent and sustainable relationship" (GRUNER; POWER, 2017). Their proposition is that, in order to deconstruct the complexity of supply chains, they should be depicted in smaller, local systems to be understood, so they can be later integrated in a simplified whole - what is similar to the demonstration performed in chapter four, for regions 6 and 7, which were later reintegrated in the whole region of Norte Pioneiro.

> System Dynamics should be combined with Mathematical Optimisation during the design of adaptive supply networks with optimal performance,

Adaptiveness, a feature essential for a system's resilience, requires improving over time, in relation to the environment (NIKOLIC; KASMIRE, 2013, p.26). This research focused on mitigation strategies for resilience, which required understanding about the system's behaviour from the interaction between causal variables, and a waste management network with optimal performance was designed considering this behaviour, as similarly performed in Hamarat et al. (2014) for policy-making and Wang et al. (2017) for water resource management. Waste generation and collection was forecast for a 21-year period, and the optimisation model adapted the network configuration every year, according to the fluctuations in the waste volumes and types, as facilities were opened and closed (or moved).

> Unintended effects related with the "common good" purpose are beneficial.

It may never be possible to predict which and when unintended effects may appear; the unintended effects consequence of a regenerative purpose are beneficial - "celebrate your emissions" (MCDONOUGH; BRAUNGART, 2013) -, like the effect of reducing underground water contamination from mining landfill waste of a degraded site, improving the quality of life of its neighbours, or the benefits of avoiding the use of chemical fertilisers. Unintended negative effects (the rebound effects) are normally linked with the technological dimension of an STS, e.g., transportation mode, or material processing.

5.2 ORIGINALITY

To the knowledge of the author, this is one of the first attempts to define a design process for supply networks with the aim of performing environmental regeneration, gathering the approaches of eco-effectiveness and eco-efficiency to drive the transition from the anthropocentrism to ecocentrism, considering both SES and STS views to support the depiction of systemic interactions. The author could not find other researches that employ DSRM explicitly to design artefacts for the transition of operations management processes towards ecocentrism and ultimately, regenerative development.

This research is also among the first initiatives to use Transdisciplinary Research as a framework for the design of artefacts in the context of Operations Management. It is normally expected that multiple concepts are combined during the design of an artefact; still, having it explicitly declared help the mindset of the designers during the process. Fitting DSRM and TR together was performed harmonically, since both methods draw from a problem-oriented focus. It is also among the first initiatives that performed systems design using resilience principles during the conceptual stage, verifying the outcome with a quantification tool like the ENA.

It is also among the first researches that explores the integration of STS and SES views, as proposed in Smith e Stirling (2010), aligned with ecocentrism. Within the scope of waste management, the author is also unaware of initiatives related with the design of integrated waste management systems which regenerates landfills. Initiatives found are limited to define waste treatment processes, optimise economic and environmental performance, and respond to demand changes. In chapter four, one step further was achieved, defining regeneration strategies and optimising these decisions.

5.3 CONTRIBUTION

Contributions were already detailed by Chapter; in this section, a few more contributions that drawn from the broader perspective of the artefacts developed in this thesis are described.

This thesis gives a contribution in both theory and practice of using DSRM for the design of artefacts aimed at environmental regeneration. For theory, theoretical basis were set for performing the design of regenerative supply networks from the broader perspective of considering the interactions with the surroundings, based in DSRM with the support of transdisciplinary research. The combination of DSR with TR led to a more effective design of complex, multidisciplinary artefacts. For practice, in chapter four it was demonstrated how environmental and economic benefits can be deployed. The class of managerial problems addressed (AKEN, 2004) was the transition of operations towards ecocentrism. Although the case explored refers to a specific situation, it contributes for the development of abstract knowledge in the transdisciplinary modelling of ecocentric systems. Chapter four also contributes to the field of multi-level analysis, where multiple levels were handled during the waste management network design, like the societal level of municipalities, and the network-level agents, i.e., waste processing plants, with transportation activities.

The RSND procedure can be applied for the design of many types of supply network: water supply network, electric power transmission, district heating, sanitary sewer, natural gas, pipeline transport, and supply chain networks. Many of these network types are normally operated by governments; through the RSND, these governments can realise the potential of achieving major benefits in the environmental dimension, overcoming targets like the ones defined in the Paris agreement on climate change, or the Sustainable Development Goals.

5.4 LIMITATIONS AND FUTURE RESEARCH

Three major challenges emerged from the researcher's lack of experience with systems thinking and lack of ability of synthesis:

- Calibrating the “holistic perspective": during the literature review process, defining excluding criteria was challenging, since the majority of the researches retrieved related somehow with the scope defined. The result is that the literature review is superficial in depth, while it covered a broad number of topics;
- Understanding the interplay between different levels of analysis: effects in lower levels from events in higher levels were difficult to be understood in the beginning, which was time consuming;
- Identifying overlap of ideas among disciplines: many times, these overlaps occurred in different levels of analysis, with different taxonomy, like Industrial Symbiosis and Reverse Logistics.

The DSRM is useful for designing artefacts, but it did not bring support to handle and integrate multiple disciplines. Time was spent before the Transdisciplinary Research framework could be found to support disciplinary integration. Further research can be performed on improving the steps within DSRM from the perspective of TR, and combining it with regenerative design and development. The RSND procedure prescribes that the regeneration purpose is linked with the network function. Although this proposition forces the designer to think in an ecocentric way, one may argue that the regenerative purpose and the network function need not to be linked: such freedom could be explored in future research.

Many dimensions identified in the literature review could not be addressed in this study. Customer demand remained out of the scope, although it plays a fundamental part. Sustainable performance indicators could have been further explored through more integrative indicators, based in Singh et al. (2009) or Hutchins e Sutherland (2008). An analogy with a vehicle seems appropriate: as a complex issue, one must rely in multiple indicators to monitor its performance, like a conductor relies upon his/hers vehicle's dashboard indicators. In chapter four, a single indicator was used to monitor the performance on each of the three dimensions of sustainability.

This is valuable as a reference, but systemic understanding is only achieved through monitoring multiple metrics. Using one indicator per dimension, although simplistic for scientists, keep it rather simple for practitioners: sometimes, multiple indicators provided by life cycle studies generate confusion. Balancing the quantity of indicators to be monitored may be seen as another relevant question for sustainable development, and its quantity defined according to the context.

This research used ENA to quantify resilience; however, the nature of the model allows only a limited verification of redundancy and specialisation of network elements. There is opportunity to enhance the quantification of resilience dimensions, like diversity Korhonen e Snäkin (2015). Other dimensions, like adaptability and flexibility remain to be conceptually and mathematically modelled, as well as understanding about how context-dependent resilience is. ENA results from chapter four confirmed to be in line with resilience principles, but raised many questions: how the definition of flow influences the results? Which unit emerges from the utilisation of each flow? What is the order of magnitude of the results found, specifically for Ascendency and Overhead? Is the range of the Window of Vitality the same for technical systems as it is for ecosystems? Substantial work must be performed before ENA can be comprehended in its entirety in the context of Operations Management, specially for supply network design.

The full implications of the complex systems approach were not explored, like self-organisation and emergence. The research is limited in this aspect, since it takes a normative approach. The procedure also shows potential to be generalised for the design of integrative Socio-Technical Systems analogue to supply networks. Future research can be performed to investigate complex systems properties in the context of regenerative design and development, through the agent-based modelling paradigm, suitable to perform investigation on self-organisation and emergence. In this direction, systems design may focus specifically on the emergence of regenerative systems, within the research stream of Design for Emergence.

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APPENDIX A – GLOSSARY OF TERMS

adaptive– “an adaptive system is a set of interacting or interdependent entities, real or abstract, forming an integrated whole that together are able to respond to environmental changes or changes in the interacting parts.” (Wikipedia contributors, 2018a)

agent– an entity who is capable of action. This term is normally used in the context of multi-agent systems modelling and simulation under the Agent-Based model paradigm.

anthropocentrism– “considering human beings as the most significant entity of the universe, interpreting or regarding the world in terms of human values and experiences.” (Merriam-Webster.com, 2018)

artefact– “an engineered artefact is a structure that, together with the context in which it is implemented, produces a process that performs the intended function” (BOTS; DAALEN, 2012)

biobased economy– Biobased economy, bioeconomy or biotechonomy refers to all economic activity derived from scientific and research activity focused on biotechnology. In other words, understanding mechanisms and processes at the genetic and molecular levels and applying this understanding to creating or improving industrial processes. (Wikipedia contributors, 2018b)

ecocentrism– “The ontological belief denies that there are any existential divisions between human and non-human nature sufficient to claim that humans are either (a) the sole bearers of intrinsic value or (b) possess greater intrinsic value than non-human nature." (Wikipedia contributors, 2018c)

biomimetics– also called biomimicry, it is “an emerging design discipline that looks to nature for sustainable design solutions. (Benyus, 1997)” (MANG; REED, 2012).

cradle-to-cradle– Cradle-to-cradle design is a biomimetic approach to the design of products and systems that models human industry on nature’s processes viewing materials as nutrients circulating in healthy, safe metabolisms.

closed-loop supply chain– “focus on taking back products from customers and recovering added value by reusing the entire product, and/or some of its modules, components, and parts.” (JR et al., 2000)

disruption– disturbance or problems which interrupt an event, activity, or process.

eco-efficiency– is the rate between economic and environmental performance. Economic performance is defined through (i) quantity of goods or services produced/provided or (ii) Net Sales. Environmental performance (i.e. impact) can be defined by (i) Energy, (ii) Materials or (iii) Water Consumption, (iv) Greenhouse Gases or (v) Substance emissions, or (vi) Ozone Depletion (VERFAILLIE; BIDWELL, 2000).

eco-effectiveness– a balanced interplay of human development with natural processes (CARRILLO-HERMOSILLA, 2012; MCDONOUGH; BRAUNGART, 2002). The eco-effectiveness approach allowing “positive externalities” to be delivered - e.g., making undesired production outcomes to become desired incomes to another, as stated in one of the principles of Upcycling*, “waste equals food” (MCDONOUGH; BRAUNGART, 2013). Eco-efficiency and eco-effectiveness can be considered as “two sides of a same coin”; their relation can be quoted as “better to go slow in the right direction than to go fast in the wrong direction”, while “better” may suggest effectiveness is more important. Combining both approaches results in “going reasonably fast in the right direction”, or “doing the right thing right”.

eco-indicator– is a pointing system based in Life Cycle Assessment to quantify environmental impact of a given product or production process. It was developed during the National Reuse of Waste Research (NOH) programme conducted in the Netherlands, involving three universities, the Ministry of Housing, Spatial Planning and the Environment (VROM) and four companies. The first version came out in 1995.

ecosystem services– are the many and varied benefits that humans freely gain from the natural environment and from properly-functioning ecosystems. They are normally divided in four categories: provisioning, e.g. the production of food or water, regulating – climate and disease control, supporting, nutrient cycles and pollination, and cultural, e.g., spiritual and recreational benefits (Wikipedia, “ecosystem services”, accessed in 12-02-2018).

emergence– In philosophy, systems theory, science, and art, emergence is a phenomenon whereby larger entities arise through interactions among smaller or simpler entities such that the larger entities exhibit properties the smaller/simpler entities do not exhibit.

externality– a cost (or benefit) incurred by a party who did not participate in the action causing the cost or benefit (to a third party). (AYRES, 2016, p.374)

food-water-energy nexus– The water, energy and food nexus means that water security, energy security and food security are inextricably linked and that actions in any one area usually have impacts in one or both of the others.

industrial symbiosis– “engages diverse organizations in a network to foster eco- innovation and long-term culture change. Creating and sharing knowledge through the network yields mutually profitable transactions for novel sourcing of required inputs, value-added destinations for non-product outputs, and improved business and technical processes” (LOMBARDI; LAYBOURN, 2012).

life-world– Refers to the human world prior to scientific knowledge. ‘Life-world’, for Schültz, “describes the structural properties of social reality as grasped by the agent.” (HADORN et al., 2008)

multi-criteria decision analysis– “or multiple-criteria decision-making (MCDM) is a sub-discipline of operations research that explicitly evaluates multiple conflicting criteria in decision making (both in daily life and in settings such as business, government and medicine).” (Wikipedia contributors, 2018e)

problem fields– “an area in which the need for knowledge related to empirical and practice-oriented questions arises within society due to an uncertain knowledge base and diffuse as well as controversial perceptions of problems” (POHL; HADORN, 2007)

product-service system (PSS)– “PSS are business models that provide for cohesive delivery of products and services. PSS models are emerging as a means to enable collaborative consumption of both products and services, with the aim of pro-environmental outcomes.” (PISCICELLI et al., 2015)

system– “a set of two or more interrelated elements with the following properties: (i) Each element has an effect on the functioning of the whole; (ii) Each element is affected by at least one other element in the system; (iii) All possible subgroups of elements also have the first two properties.” (ACKOFF, 1981)

upcycling– is the process of transforming by-products, waste materials, useless, or unwanted products into new materials or products of better quality or for better environmental value. (Wikipedia contributors, 2018g)

APPENDIX B – SUMMARY OF FINDINGS

Source	Main Concepts	Main Findings
Bergendahl et al. (2018)	Food-Water-Energy nexus* / Transdisciplinarity / Ecological Modernisation / Sustainable Supply Chain	- Efforts to improve the effectiveness of a complex system require collaboration between multiple parties, in different levels and areas of expertise. - The large variety of disciplines evolving processes and decision-making can provide consistent, holistic solutions, in the dimensions of technology and society, if transdisciplinary thinking is embraced.
Souza et al. (2019)	Ecological Economics / Sustainable Supply Chain Design / Resilience*	- Eco-efficiency may interfere with network resilience, as the former decrease the number of interconnections in the network. - Using Ecosystem Network Analysis may be useful for decision-making processes, during comparison among different network configurations.

Source	**Main Concepts**	**Main Findings**
Gruner e Power (2017)	Biomimicry / Ecosystem Principles / Sustainable Supply Chain / Industrial Ecology	- Knowledge of combining ecological principles, and about how they inter-relate and reinforce each other, can lead to more radical, new operating models. - Ecosystems have become increasingly vulnerable to change; socio-ecological intergradation mimics natural ecosystems and protects ecosystem services for organisational development.
Jonkman et al. (2017)	Process Design / Supply Chain Design / Biobased Economy*	Taking the whole product portfolio into account for the design of a food production process improves Supply Chain performance
Niero et al. (2017)	Circular Economy / Operations Management / Eco-efficiency and eco-effectiveness	- From a business perspective, product design plays a key role in the implementation of circular economy strategies. - The closed-loop supply business model must be included in the product design procedure, through e.g. a green value network business model which incorporates both economic and environmental perspectives.
Levalle e Nof (2017)	Complex Adaptive Systems / Resilience* / Sustainable Supply Network	- Resilience is an inherent ability of SN agents, and/or an emergent ability of supply networks, related to coping with disruptions caused by undesired events - but not necessarily unforeseen. - Resilience involves two dimensions: Supply Network structure (i.e., its topology), and control protocols.

Source	**Main Concepts**	**Main Findings**
Banasik et al. (2016)	Closed-loop Sustainable Supply Chain Design / Eco-efficiency* / 3R	- When waste value is recovered as much as possible, win-win solutions are achieved.
Fahimnia e Jabbarzadeh (2016)	Resilience / Sustainable Supply Chain / Dynamic Analysis	- A resilient, sustainable SC, developed through a dynamic sustainability trade-off analysis, was able to satisfy market demand with only a slight increase in cost. Environmental and social performance of the SC remained almost unaffected in disruptions.
Joore e Brezet (2015)	Multilevel Design Process / Product-Service System / Systems Engineering	- The development of new sustainable products and product-service systems is interwoven with developments in the broader socio-technical and societal context in which these new products and product-service systems will be functioning. - Distinguishing between the various system levels helps to determine which requirements should be met during the design process.
Behdani (2013)	Resilience* / Supply Chain / System Dynamics / Complex Adaptive Systems	A supply chain disruption management model must capture the social and physical characteristics of the supply chain and allow for alterations.

APPENDIX C – WASTE NETWORK DESIGN PARAMETERS

Table C1: Municipalities location and population in the Norte Pioneiro, organized by sub-region. (continues)

Region[1]	Municipality	Population[2]	Pop. Fraction	Coordinate X[3]	Coordinate Y[3]
R6	Assaí	16,212	2.94%	516.209677	7415.142466
	Bandeirantes	32,562	5.90%	564.767839	7444.162865
	Congonhinhas	8,736	1.58%	545.559105	7395.399347
	Cornélio Procópio	8.80%	48,615	536.161809	7436.387167
	Curiúva	14,817	2.68%	555.080206	7342.069217
	Figueira	8,268	1.50%	560.787162	7362.344608
	Itambaracá	6,852	1.24%	560.826964	7454.389028
	Leópolis	4,165	0.75%	525.491513	7447.602510
	Nova América da Colina	3,553	0.64%	528.880136	7419.858868
	Nova Fátima	8,359	1.51%	544.550061	7408.564626
	Nova Santa Bárbara	4,163	0.75%	542.316170	7391.626469
	Rancho Alegre	3,990	0.72%	508.905600	7448.728575
	Santa Amélia	3,684	0.67%	558.896772	7426.935161
	Santa Cecília do Pavão	0.65%	3,597	522.090508	7399.205361
	Santa Mariana	12,432	2.25%	549.278887	7439.701481
	Santo Antônio do Paraíso	2,333	0.42%	536.190744	7401.791292

[1] according to Engebio (2013);

[2] data from IBGE (2010);

[3] data from IPARDES (2010), coordinates converted to Universal Transverse Mercator (UTM) with www.zonums.com, unit: km.

Table C1: Municipalities location and population in the Norte Pioneiro, organized by sub-region. (continued)

Region[1]	Municipality	Population[2]	Pop. Fraction	Coordinate X[3]	Coordinate Y[3]
	São Jerônimo da Serra	11,553	2.09%	526.387077	7375.918481
	São Sebastião da Amoreira	8,952	1.62%	524.397033	7404.952348
	Sapopema	6,908	1.25%	542.720019	7355.581974
	Sertaneja	5,724	1.04%	516.563350	7452.381344
	Uraí	11,695	2.12%	520.835926	7434.602187
R7	Abatiá	7,823	1.42%	570.298654	7422.703072
	Andirá	20,822	3.77%	578.996848	7450.675585
	Barra do Jacaré	2,821	0.51%	583.823266	7443.514586
	Cambará	25,287	4.58%	594.908162	7451.044602
R7	Carlópolis	14,337	2.60%	630.684426	7408.851579
	Conselheiro Mairinck	3,831	0.69%	584.803677	7386.520752
	Guapirama	3,950	0.72%	598.035759	7399.017193
	Ibaiti	30,888	5.59%	582.710225	7362.297110
	Jaboti	5,197	0.94%	594.186251	7373.883696
	Jacarezinho	40,253	7.29%	605.491539	7438.333436
	Japira	5,071	0.92%	587.741129	7366.204250
	Joaquim Távora	11,544	2.09%	611.833203	7400.763875
	Jundiaí do Sul	3,456	0.63%	576.868578	7407.939247
	Pinhalão	6,425	1.16%	596.188513	7368.426540
	Quatiguá	7,410	1.34%	610.868708	7393.266351
	Ribeirão Claro	10,949	1.98%	627.100502	7434.443188
	Ribeirão do Pinhal	13,646	2.47%	565.731163	7411.222333
	Salto do Itararé	5,201	0.94%	640.204294	7389.230880

[1] according to Engebio (2013);

[2] data from IBGE (2010);

[3] data from IPARDES (2010), coordinates converted to Universal Transverse Mercator (UTM) with www.zonums.com, unit: km.

Table C1: Municipalities location and population in the Norte Pioneiro, organized by sub-region. (continued)

Region[1]	Municipality	Population[2]	Pop. Fraction	Coordinate X[3]	Coordinate Y[3]
	Santana do Itararé	5,267	0.95%	639.700686	7372.224645
	Santo Antônio da Platina	45,562	8.25%	594.363745	7423.522685
	São José da Boa Vista	6,539	1.18%	637.181486	7354.437659
	Siqueira Campos	20,303	3.68%	618.895398	7379.730944
	Tomazina	8,619	1.56%	607.011133	7369.919205
	Wenceslau Braz	19,847	3.59%	621.895134	7359.220123
	TOTAL	**552,218**	**100.00%**		

[1] according to Engebio (2013);

[2] data from IBGE (2010);

[3] data from IPARDES (2010), coordinates converted to Universal Transverse Mercator (UTM) with www.zonums.com, unit: km.

Table C2: Degraded sites in the Norte Pioneiro. (continues)

Region	Municipality/ Site[1]#	Site Type[1]	Area[2] (ha)	Status[1]	Waste Stock[3]	Coordinate X (WGS)[2]	Coordinate Y (WGS)[2]
R6	Assaí	Disposal Site	3.25	Closed	18.51	-23.392576	-50.845501
	Congonhinhas	Controlled Landfill	3.05	Closed	6.88	-23.530000	-50.520000
	Cornélio Procópio	Dumping Ground	8.70	Closed	100.00	-23.317821	-50.599605
	Itambaracá	Dumping Ground	2.80	Operating	9.00	-23.030422	-50.427931
	Nova Santa Bárbara	Unknown	1.80	Unknown	9.63	-23.593096	-50.718922
	Santa Mariana	Dumping Ground	4.40	Closed	12.96	-23.147767	-50.505527
	São Sebastião da Amoreira	Dumping Ground	5.10	Closed	10.70	-23.479370	-50.780204
R7	Abatiá	Controlled Landfill	3.15	Operating	11.40	-23.301193	-50.335378
	Andirá	Controlled Landfill	8.05	Operating	40.00	-23.068009	-50.254676
	Carlópolis	Dumping Ground	8.30	Operating	24.00	-23.422278	-49.749184
	Ibaiti	Controlled Landfill	5.00	Closed	59.23	-23.869183	-50.220874
	Jacarezinho 1	Dumping Ground	4.33	Closed	11.74	-23.188780	-49.972307
	Jacarezinho 2	Dumping Ground	18.00	Closed	48.80	-23.170000	-49.960000
	Jacarezinho 3	Dumping Ground	2.85	Closed	7.73	-23.150000	-49.970000
	Jacarezinho 4	Controlled Landfill	11.98	Operating	32.48	-23.133688	-49.925541
	Jacarezinho 5	Disposal Site	6.00	Closed	16.27	-23.143325	-49.960338

[1] data from Envex e Engebio (2018a);

[2] determined based in Google Maps.

[3] estimated from Google Maps and historical data from Brasil (2016), in kilotonnes.

Degraded sites in the Norte Pioneiro. (continued)

Region	Municipality/ Site[1]#	Site Type[1]	Area[2] (ha)	Status[1]	Waste Stock[3]	Coordinate X (WGS)	Coordinate Y (WGS)
R7	Pinhalão	Sanitary Landfill without license	10.50	Operating	15.50	-23.789084	-50.090112
	Ribeirão do Pinhal	Sanitary Landfill without license	3.45	Closed	22.25	-23.458579	-50.372490
	Salto do Itararé	Dumping Ground	1.76	Operating	21.45	-23.609345	-49.648130
	Santo Antônio da Platina	Dumping Ground	1.50	Closed	78.24	-23.329329	-50.126391
	Siqueira Campos	Dumping Ground	5.00	Closed	38.30	-23.706490	-49.794241
	Wenceslau Braz 1	Dumping Ground	2.10	Operating	49.00	-23.903861	-49.812594
	Wenceslau Braz 2	Dumping Ground	5.70	Closed	10.00	-23.905835	-49.813229

[1] data from Envex e Engebio (2018a);

[2] determined based in Google Maps.

[3] estimated from Google Maps and historical data from Brasil (2016), in kilotonnes.

Table C3: Facilities CAPEX and GHG "capital" emissions (CAGEM).

Facility Type	Investment Cost (kBRL)	CAGEM (tCO$_{2eq}$/unit)	Capacity	Unit	Jobs
Recyclables Sorting Centre	1,053[1]	1,758[2]	4,200[1]	tonnes/year	117[1]
Aerobic Composting Centre - Large	1,010[3]	703.2[2]	8,640[3]	tonnes/year	10[10]
Aerobic Composting Centre - Small	100[4]	140.6[2]	675[4]	tonnes/year	5[10]
Anaerobic Digestion Plant	55,000[5]	8,790[2]	32,400[6]	tonnes/year	15[10]
Gasification Plant	17,810[7]	7,032[2]	20,000[8]	tonnes/year	8[10]
Sanitary Landfill	543,5[9]	4,465[2]	157,315[9]	tonnes	4[9]

[1] Xavier (2013);

[2] Based in Medeiros et al. (2018) for a value of 351.6 kgCO$_{2}eq$/m^{2} multiplied by the area from: Google Maps, for UVR Campo Magro (RSC), CSEnergia (AnDP), Lahti Energia Oy Finland (GP); Pires (2011) (bAeCC, sAeCC = bAeCC/5) and Ribeiro (2011) (SLF).

[3] Pires (2011); [4] Based in Neto (2006); [5] Rios (2014); [6] CSBioenergia (2015); [7] Paiva (2015); [8] Based in Paiva (2015); [9] Ribeiro (2011); [10] Estimated.

Matrix (C3) linking facilities that can exchange waste flows.

$$\mathbf{link_{k,k\prime}} = \begin{array}{c c c c c c c} \text{RSC} & \text{bAeCC} & \text{sAeCC} & \text{AnDP} & \text{GP} & \text{SLF} & \\ \left[\begin{array}{c} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{array}\right. & \begin{array}{c} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{array} & \begin{array}{c} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{array} & \begin{array}{c} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{array} & \begin{array}{c} 1 \\ 1 \\ 1 \\ 1 \\ 0 \\ 0 \end{array} & \left.\begin{array}{c} 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 0 \end{array}\right] & \begin{array}{l} \text{RSC} \\ \text{bAeCC} \\ \text{sAeCC} \\ \text{AnDP} \\ \text{GP} \\ \text{SLF} \end{array} \end{array} \tag{C3}$$

Table C4: Regenerated sites Parameters. (continues)

Degraded Site	Regeneration	Expenditures[2]		Yearly	Emissions[3]		Av./Cap.
	Strategy[1]	OPEX[5]	CAPEX[6]	Revenues[2,7]	OGEM[8]	CAGEM[9]	GHG[4,10]
Abatiá	R	16,250	55,963	-	-	788	56,700
Andirá	SF	286,944	143,017	-	26,645	2,013	144,900
Assaí	R	43,500	57,740	-	-	813	58,500
Carlópolis	R	14,000	415,000	-	-	4,150	24,900
Congonhinhas	R	9,000	6,710,000	366,366	-	2,562,000	871,080
Cornélio Procópio	P	1,500	154,565	-	286	2,175	156,600
Ibaiti	SF	479,808	11,000,000	600,600	44,554	4,200,000	1,428,000
Itambaracá	R	15,750	49,745	-	-	700	50,400
Jacarezinho 1	R	40,250	216,500	-	-	2,165	12,990
Jacarezinho 2	P	1,500	39,600,000	2,162,160	540	15,120,000	5,140,800
Jacarezinho 3	SF	470,400	142,500	-	43,680	1,425	8,550
Jacarezinho 4	P	1,500	26,356,000	1,439,038	281	10,063,200	3,421,488
Jacarezinho 5	SF	1,693,440	13,200,000	720,720.00	157,248	5,040,000	1,713,600

[1] SF - Solar Farms; R - Reforestation; P - Parks.

[2] In BRL; [3] In $kgCO_{2eq}$/year (OGEM) and $kgCO_{2eq}$/unit (CAGEM); [4] Avoided or Captured GHG, in $kgCO_{2eq}$/year; [5] R and P: estimated. SF: based in CanalEnergia.com.br (2017).

[6] R: based in Fontenele (2015), SF: based in UCSUSA (2013), P: estimated.

[7] SF: based in CanalEnergia.com.br (2017); [8] SF: based in NREL (2012), R and P: estimated.

[9] SF: based in UCSUSA (2013), R and P: estimated.

[10] SF: based in King e Gutberlet (2016), R: based in NZFSA (2018), P: estimated.

Table C4: Regenerated sites Parameters. (continued)

Degraded Site	Regeneration Strategy[1]	Expenditures[2]		Yearly Revenues[2]	Emissions[3]		Av./Cap. GHG[4]
		OPEX	CAPEX		OGEM	CAGEM	
Nova Santa Bárbara	P	1,500	31,979	-	185	450	32,400
Pinhalão	SF	1,127,078	186,545	-	104,657	2,625	189,000
Ribeirão do Pinhal	SF	564,480	61,293	-	52,416	863	62,100
Salto do Itararé	R	52,500	31,268	-	-	440	31,680
Santa Mariana	R	17,250	220,000	-	-	2,200	13,200
Santo Antônio da Platina	R	8,800	3,300,000	180,180	-	1,260,000	428,400
São Sebastião da Amoreira	SF	141,120	11,220,000	612,612	13,104	4,284,000	1,456,560
Siqueira Campos	R	25,000	88,831	-	-	1,250	90,000
Wenceslau Braz 1	R	10,500	37,309	-	-	525	37,800
Wenceslau Braz 2	R	28,500	101,267	-	-	1,425	102,600

[1] SF - Solar Farms; R - Reforestation; P - Parks.

[2]In BRL; [3]In kgCO$_{2eq}$/year (OGEM) and kgCO$_{2eq}$/unit (CAGEM); [4]Avoided or Captured GHG, in kgCO$_{2eq}$/year; [5] R and P: estimated. SF: based in CanalEnergia.com.br (2017).

[6] R: based in Fontenele (2015), SF: based in UCSUSA (2013), P: estimated.

[7] SF: based in CanalEnergia.com.br (2017); [8] SF: based in NREL (2012), R and P: estimated.

[9] SF: based in UCSUSA (2013), R and P: estimated.

[10] SF: based in King e Gutberlet (2016), R: based in NZFSA (2018), P: estimated.

Table C5: Waste processing data of existing RSCs and SLFs. (continues)

Region	Facility name	Type/Code	OPEX[1]	Capacity[2,3]
R6	Barracão da Reciclagem Assaí	RSC01	145.00[3]	530
R6	Associação de catadores "Futuro do amanhã", Bandeirantes	RSC02	100.00[3]	100
R6	Associação de Catadores de Congonhinhas – ACMRC Congonhinhas	RSC03	312.00[3]	160
R6	ARECOP Cornélio Procópio	RSC04	252.00[3]	270
R6	ACREVE Curiúva	RSC05	145.00[4]	480
R6	ctmar Nova Santa Bárbara	RSC06	200.00[4]	15
R6	ASCAMAR Associação Catadores de Santa Cecília do Pavão	RSC07	200.00[4]	60
R6	Unidade de Triagem São Jerônimo da Serra	RSC08	160.00[4]	300
R7	ATAR Abatiá	RSC09	200.00[4]	110
R7	Associação RECRIAR Andirá	RSC10	200.00[3]	350
R7	BARRACÃO TRIAGEM Ibaiti	RSC11	770.00[3]	10
R7	Unidade de Triagem Coleta Seletiva Jaboti	RSC12	200.00[4]	2,500
R7	Assomarja Jacarezinho	RSC13	200.00[4]	2,500
R7	MATERIAIS RECICLAVEIS Joaquim Távora	RSC14	200.00[4]	120
R7	Usina de Reciclagem de Lixo Ribeirão Claro	RSC15	200.00[4]	2,000
R7	Coleta seletiva Ribeirão do Pinhal	RSC16	200.00[4]	300
R7	ASAGASI Santana do Itararé	RSC17	200.00[4]	200
R7	Associação de Promoção Humana Platinense S. A. da Platina	RSC18	900.00[3]	1100
R7	Usina de Triagem Siqueira Campos	RSC19	200.00[4]	250

[1] in BRL per tonne of waste; [2] in tonnes per year for RSCs, and total tonnes for SLFs.

[3] Values from Brasil (2016); [4] Estimated.

Table C5: Waste processing data of existing RSCs and SLFs. (continued)

Region	Facility name	Type/Code	OPEX[1]	Capacity[2,3]
R7	Usina de Triagem Wenceslau Braz	RSC20	589.10[3]	1,100
R6	SLF - Assaí	SLF1	240.00[3]	103,646
R6	SLF - Bandeirantes	SLF2	113.60[3]	75,926
R6	SLF - Cornélio Procópio	SLF3	240.00[4]	43,680
R6	SLF - Curiúva	SLF4	87.67[3]	16,520
R7	SLF - Cambará	SLF5	240.00[4]	50,000
R7	SLF - Japira	SLF6	150.00[4]	80,000
R7	SLF - Joaquim Távora	SLF7	150.00[4]	82,194

[1] in BRL per tonne of waste; [2] in tonnes per year for RSCs, and total tonnes for SLFs.

[3] Values from Brasil (2016); [4] Estimated.

Table C6: Waste processing parameters.

Recovery Process	Processing Cost*	GHG Emissions**	Outputs						
			Type	Rate	Unit (X/tonne)#	Selling Price	Unit (BRL/Y)#	GHG avoided	Unit ($kgCO_2eq$/Z)#
Windrow Composting	16.94[1]	118.00[2]	Compost	0.659[3]	tonnes	179.00[4]	tonne	418.15[5]	tonne
Anaerobic Digestion	262.35[6]	76.00[2]	Electricity	0.648[6]	MWh	251.00[7]	MWh	340[8]	MWh
			Digestate	0.659[2]	tonnes	190.00[4]	tonne	418.15[5]	tonne
Gasification	141.50[9]	412.00[10]	Electricity	0.591[9]	MWh	235.95[11]	MWh	340[8]	MWh
			Ashes	0.140[17]	tonnes	16.90[18]	tonne	1.45[19]	tonne
Recyclables Sorting	415.98[12]	19.40[13]	Recyclables	0.8764[14]	tonnes	-	tonne		
			Plastic	0.3710[14]	tonnes	691.50[14]	tonne	459[15]	kg
			Paper	0.3720[14]	tonnes	315.00[14]	tonne	1024[15]	kg
			Metals	0.1140[14]	tonnes	1955.00[14]	tonne	3577[15]	kg
			Glass	0.0194[14]	tonnes	221.25[14]	tonne	314[15]	kg
			Other	0.1236[14]	tonnes	526.00[14]	tonne	325[15]	kg
Landfilling:									
Raw Waste	119.23[16]	150.00	-	-	-	-	-		
Ashes		30.00##	-	-	-	-	-		

* BRL/tonne of waste; ** $kgCO_{2eq}$/tonne of waste processed.

unit is complete after replacing X, Y or Z by the unit in the respective field.

Assumed that emissions drop by a factor of 5 from organic waste to ashes, based in Lombardi e Laybourn (2012).

[1] Pires (2011); [2]Phong (2012); [3]Salemdeeb et al. (2017); [4]MFRural (2017); [5]Menikpura et al. (2013); [6] Based in CSBioenergia (2015) and CSBioenergia (2016); [7]UNICA (2016); [8]King e Gutberlet (2016); [9]Based in Paiva (2015); [10] Kumar e Samadder (2017); [11]Assumed; [12]Xavier (2013); [13]Liu et al. (2017); [14] Based in Xavier (2013); [15]Turner et al. (2015); [16] Based in Ribeiro (2011); [17] Based in Jimenez et al. (2017); [18] Based in CBIC (2018), BRADESCO (2017), CRQ-IV (2017), Kajaste e Hurme (2016); [19] Based in Kajaste e Hurme (2016).

Year	RSC CODE									
	RSC01	RSC02	RSC03	RSC04	RSC05	RSC06	RSC07	RSC08	RSC09	RSC10
2018	0.8097	0.9600	0.7000	0.7000	0.7000	0.7000	0.8571	0.8667	0.8333	0.9385
2019	0.8097	0.9600	0.7000	0.7000	0.7000	0.7000	0.8571	0.8667	0.8333	0.9385
2020	0.8097	0.9600	0.7000	0.7000	0.7000	0.7000	0.8571	0.8667	0.8333	0.9385
2021	0.8097	0.9600	0.7000	0.7000	0.7000	0.7000	0.8571	0.8667	0.8333	0.9385
2022	0.8097	0.9600	0.7000	0.7000	0.7000	0.7000	0.8571	0.8667	0.8333	0.9385
2023	0.8097	0.9600	0.7500	0.7500	0.7500	0.7500	0.8571	0.8667	0.8333	0.9385
2024	0.8097	0.9600	0.7500	0.7500	0.7500	0.7500	0.8571	0.8667	0.8333	0.9385
2025	0.8097	0.9600	0.7500	0.7500	0.7500	0.7500	0.8571	0.8667	0.8333	0.9385
2026	0.8097	0.9600	0.7500	0.7500	0.7500	0.7500	0.8571	0.8667	0.8333	0.9385
2027	0.8097	0.9600	0.7500	0.7500	0.7500	0.7500	0.8571	0.8667	0.8333	0.9385
2028	0.8097	0.9600	0.7500	0.7500	0.7500	0.7500	0.8571	0.8667	0.8333	0.9385
2029	0.8097	0.9600	0.7500	0.7500	0.7500	0.7500	0.8571	0.8667	0.8333	0.9385
2030	0.8097	0.9600	0.7500	0.7500	0.7500	0.7500	0.8571	0.8667	0.8333	0.9385
2031	0.8097	0.9600	0.8000	0.8000	0.8000	0.8000	0.8571	0.8667	0.8333	0.9385
2032	0.8097	0.9600	0.8000	0.8000	0.8000	0.8000	0.8571	0.8667	0.8333	0.9385
2033	0.8097	0.9600	0.8000	0.8000	0.8000	0.8000	0.8571	0.8667	0.8333	0.9385
2034	0.8097	0.9600	0.8000	0.8000	0.8000	0.8000	0.8571	0.8667	0.8333	0.9385
2035	0.8097	0.9600	0.8000	0.8000	0.8000	0.8000	0.8571	0.8667	0.8333	0.9385
2036	0.8097	0.9600	0.8000	0.8000	0.8000	0.8000	0.8571	0.8667	0.8333	0.9385
2037	0.8097	0.9600	0.8000	0.8000	0.8000	0.8000	0.8571	0.8667	0.8333	0.9385
2038	0.9000	0.9600	0.9000	0.9000	0.9000	0.9000	0.9000	0.9000	0.9000	0.9385

Year	RSC CODE									
	RSC11	RSC12	RSC13	RSC14	RSC15	RSC16	RSC17	RSC18	RSC19	RSC20
2018	0.7921	0.7000	0.7000	0.8000	0.8959	0.8100	0.8000	0.9167	0.9600	0.8818
2019	0.7921	0.7000	0.7000	0.8000	0.8959	0.8100	0.8000	0.9167	0.9600	0.8818
2020	0.7921	0.7000	0.7000	0.8000	0.8959	0.8100	0.8000	0.9167	0.9600	0.8818
2021	0.7921	0.7000	0.7000	0.8000	0.8959	0.8100	0.8000	0.9167	0.9600	0.8818
2022	0.7921	0.7000	0.7000	0.8000	0.8959	0.8100	0.8000	0.9167	0.9600	0.8818
2023	0.7921	0.7500	0.7500	0.8000	0.8959	0.8100	0.8000	0.9167	0.9600	0.8818
2024	0.7921	0.7500	0.7500	0.8000	0.8959	0.8100	0.8000	0.9167	0.9600	0.8818
2025	0.7921	0.7500	0.7500	0.8000	0.8959	0.8100	0.8000	0.9167	0.9600	0.8818
2026	0.7921	0.7500	0.7500	0.8000	0.8959	0.8100	0.8000	0.9167	0.9600	0.8818
2027	0.7921	0.7500	0.7500	0.8000	0.8959	0.8100	0.8000	0.9167	0.9600	0.8818
2028	0.7921	0.7500	0.7500	0.8000	0.8959	0.8100	0.8000	0.9167	0.9600	0.8818
2029	0.7921	0.7500	0.7500	0.8000	0.8959	0.8100	0.8000	0.9167	0.9600	0.8818
2030	0.7921	0.7500	0.7500	0.8000	0.8959	0.8100	0.8000	0.9167	0.9600	0.8818
2031	0.8000	0.8000	0.8000	0.8000	0.8959	0.8100	0.8000	0.9167	0.9600	0.8818
2032	0.8000	0.8000	0.8000	0.8000	0.8959	0.8100	0.8000	0.9167	0.9600	0.8818
2033	0.8000	0.8000	0.8000	0.8000	0.8959	0.8100	0.8000	0.9167	0.9600	0.8818
2034	0.8000	0.8000	0.8000	0.8000	0.8959	0.8100	0.8000	0.9167	0.9600	0.8818
2035	0.8000	0.8000	0.8000	0.8000	0.8959	0.8100	0.8000	0.9167	0.9600	0.8818
2036	0.8000	0.8000	0.8000	0.8000	0.8959	0.8100	0.8000	0.9167	0.9600	0.8818
2037	0.8000	0.8000	0.8000	0.8000	0.8959	0.8100	0.8000	0.9167	0.9600	0.8818
2038	0.9000	0.9000	0.9000	0.9000	0.9000	0.9000	0.9000	0.9167	0.9600	0.9000

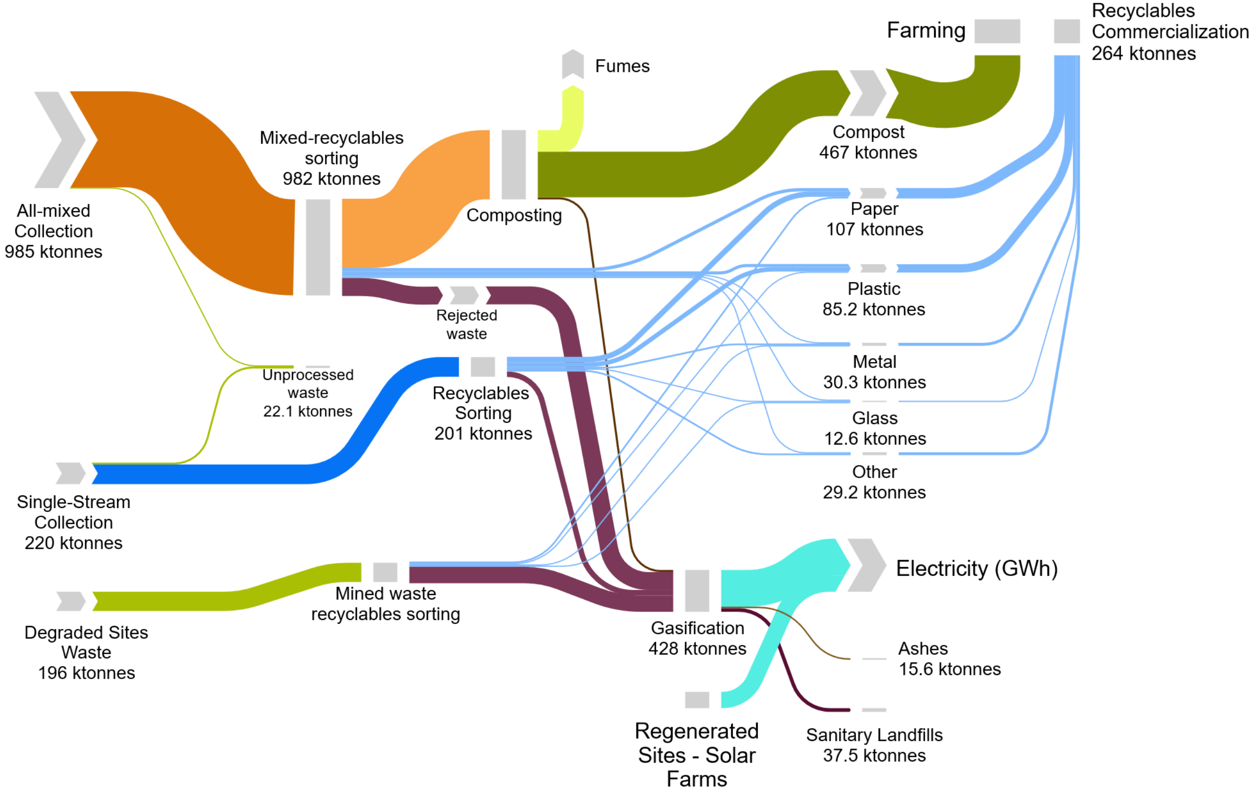
* Values for RSC01, RSC02, RSC07, RSC08, RSC09, RSC10, RSC11, RSC15, RSC16, RSC18, RSC19 and RSC20 were calculated from data in Brasil (2016). Values for RSC03, RSC04, RSC05, RSC06, RSC12, RSC13, RSC14 and RSC17 were estimated.

Table C7: Sorting rates for existing RSCs per year, in kg/kg*.

Year	Ashes status	
	Aggregate	Landfill Waste
2018-2020	0%	100%
2021-2023	10%	90%
2024-2031	30%	70%
2032-2038	50%	50%

Table C8: Evolution of the destination of ashes for each year, in kg/kg.

APPENDIX D – SANKEY DIAGRAM: PROFIT, REGION 6, SCENARIO SR



APPENDIX E – SANKEY DIAGRAM: NET GHG, REGION 6, SCENARIO SR