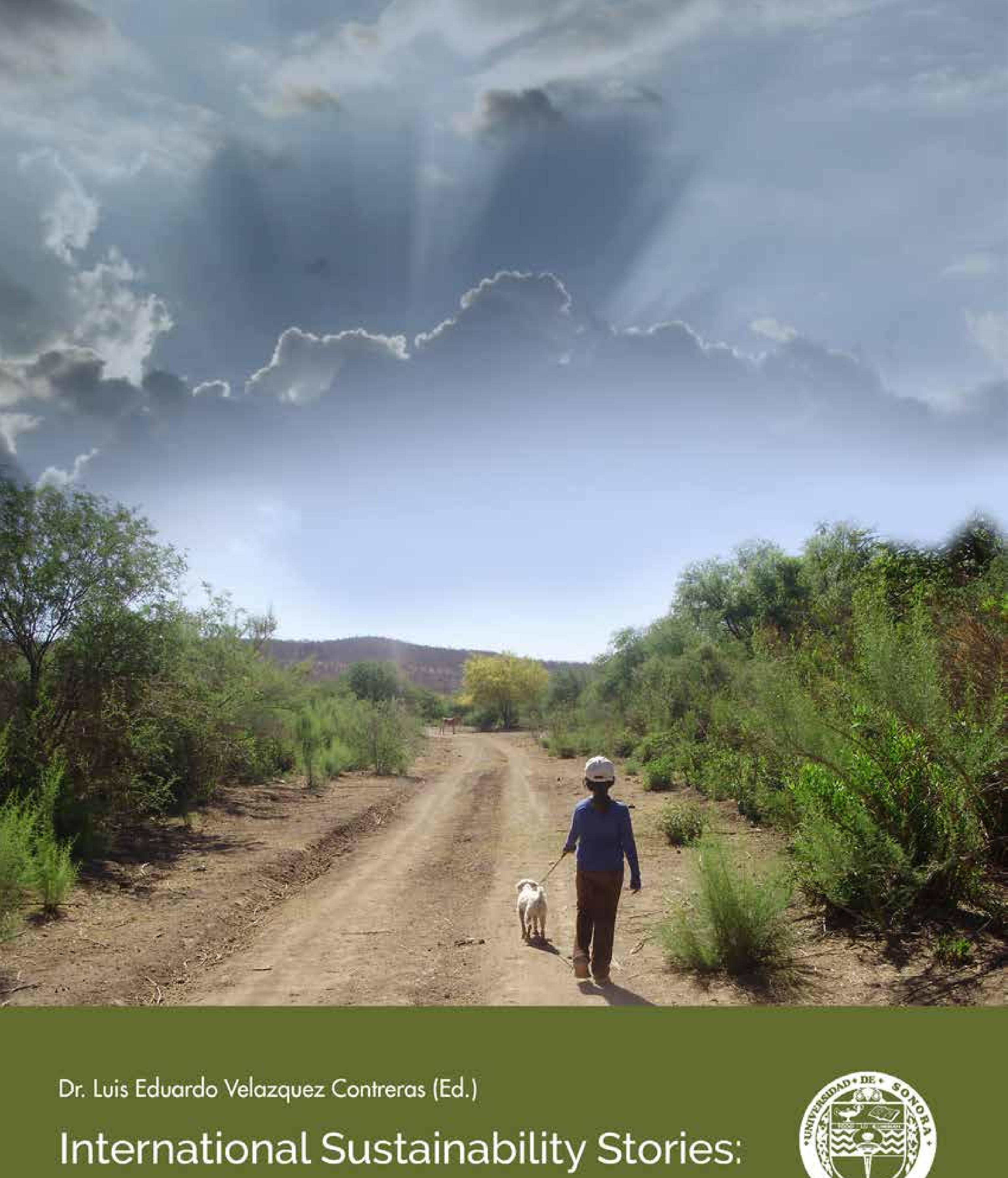


Dr. Luis Eduardo Velazquez Contreras (Ed.)

International Sustainability Stories: Enhancing Good Practices

"El saber de mis hijos hará mi grandeza"

International Sustainability Stories:
Enhancing Good Practices

Editor Luis Velazquez
Kenneth Geiser
Leenard Baas †
Rafael Moure-Eraso
Anila Bello
Alicia McCarthy
Dhimiter Bello
Biagio F. Giannetti
Cecília Maria Villas Bôas de Almeida
Feni Dalano Roosevelt Agostinho
José Fernando Faro
Fábio Sevegnani
Joost Platje
Tino Schuette
Marco Rieckmann
Markus Will
Javier Esquer
Nora Munguia
David Zepeda
Romain Sacchi
Arne Remmen

"El saber de mis hijos hará mi grandeza"

International Sustainability Stories: Enhancing Good Practices

Coordinator
Dr. Luis Eduardo Velazquez Contreras

Blvd. Luis Encinas y Rosales s/n C.P. 83000
Hermosillo, Sonora, México
www.uson.mx
ISBN: XXX-XXXXX-XXXXX

PRESENTATION

One of the most pressing issues of our time is sustainability. Since 1992, the University of Sonora has promoted sustainability and encouraged climate friendly behaviors inside and outside the university. Because of these fruitful efforts, the university has been considered an international icon of sustainability. This e-book represents the highpoint of these efforts.

I really hope that by reading this e-book, students will gain knowledge about how to foster and develop stewardships around sustainability. One of the issues that is especially interesting and timely in this e-book is its multidisciplinary approach to the issue of sustainability. The chapters in this e-book were written by the leading scholars on sustainability from around the world. For this, I cannot thank them enough.

As a former Rector of the University of Sonora, it is a pleasure to have made this International Sustainability Stories e-book available free. This e-book is essential reading for the entire sustainability science community as well as to bachelor and graduate students interested in learning about and taking actionable steps toward sustainability.

DR. HERIBERTO GRIJALVA MONTEVERDE
FORMER RECTOR OF THE UNIVERSITY OF SONORA
(2013-2017)

SUSTAINABILITY INSTITUTIONAL COMMITMENT

In the future, the University of Sonora will increase its efforts to engage internationally. Such efforts are vitally important to our institution because they have the opportunity to influence the ways in which our students engage in the world. Internationalization engagement is a key priority not only for the University of Sonora, but also for many other Mexican higher education institutions. Internationalization engagement is facing some relatively new challenges that cannot be understated. Therefore, these endeavors require the cooperation and willingness of students, professors, staff, and authorities.

At our institution, we already have great examples of international collaborations. For example, the Sustainable Development Group has had a longstanding history of working toward sustainability in concert with many collaborators from higher education institutions across the globe. The e-book, "International Sustainability Stories: Enhancing Good Practices" is an excellent example of the outcome of such international engagement efforts. The e-book contains case studies written by senior scientists from around the world to inspire students and professors to maintain and initiate sustainability efforts.

As a rector of the University of Sonora, I would like to thank all of you who helped to make this e-book, especially to each of the authors. I wish you much success in this.

Finally, I want to reaffirm the complete institutional commitment to collaborate nationally and internationally with partners to foster sustainability at a local and global scale.

DR. ENRIQUE FERNANDO VELAZQUEZ CONTRERAS

RECTOR OF THE UNIVERSITY OF SONORA

(2017-2021)

BIOGRAPHIES

Luis Velazquez has more of 25 years of experience as Industrial Engineer and since 1994 he has served as Director of Sustainable Development Group in the Engineering College at the University of Sonora. He is senior researcher in the Sustainability, Cleaner Production and Pollution Prevention. Dr. Velazquez holds a doctoral degree in the major of Cleaner Production and Pollution Prevention from the University of Massachusetts Lowell. Currently, he is professor and researcher in the University of Sonora in Mexico and adjunct professor in the University of Massachusetts Lowell. He has been editor of other sustainability books and author of several sustainability articles published in top journals.

Kenneth Geiser is Professor Emeritus of Work Environment at the University of Massachusetts Lowell, Founder and past Codirector of the Lowell Center for Sustainable Production, and the author of Materials Matter: Toward a Sustainable Materials Policy. One of the authors of the Massachusetts Toxics Use Reduction Act, he was Director of the Massachusetts Toxics Use Reduction Institute for thirteen years. At the University he taught various policy courses in the Department of Work Environment, chaired the University Committee of Federated Centers and Institutes, co-chaired the Faculty Development Committee, served in the Faculty Senate, and acted as Special Assistant to the Provost for Research. His research and writing focus on cleaner production, pollution prevention, toxic chemicals management, international chemicals policy, safer technologies, and green chemistry. In 2001, he completed a book, Materials Matter: Towards a Sustainable Materials Policy and, in 2015, a second book, Chemicals without Harm, Policies for a Sustainable World, both published by MIT Press. Dr. Geiser is one of the primary author's of the United Nation's Environment Program's Global Chemicals Outlook and has served as a Project Coordinator for the United Nations Environment Program's Chemicals in Products Project.

Leenard Baas was a professor in Industrial Ecology at the division of Environmental Technology and Management in the Department of Management and Engineering at Linköping University since May 2009, emeritus since June 2013. He was supervisor and member of the management board of the International Off-Campus Ph.D. Programme on Cleaner Production, Cleaner Products, Industrial Ecology & Sustainability at Erasmus University Rotterdam, the Netherlands. He performed research on cleaner production since 1988 and on industrial ecology since 1994 at Erasmus University Rotterdam until May 2009. He also performed research on industrial ecology and renewable energy at Linköping University since 2009. He was a member of the editorial boards of Elsevier's Journal of Cleaner Production and the International Journal on Performability Engineering in India. He is considered by most of the sustainability experts as one of the pioneers of Cleaner Production and Pollution Prevention in the world.

Rafael Moure-Eraso is an Emeritus Professor of the University of Massachusetts Lowell. He received his doctorate from the University of Cincinnati (Ohio, U.S.) in 1982, and he has been a visiting professor at various universities in Mexico and United States. He was appointed Chairperson of the U.S.

Chemical Safety and Hazard Investigation Board (CSB) by President Barack Obama for a five year period (2010-15). His main research interests are in occupational safety and health and public policy. He is currently a Fulbright Scholar in the roster of U.S. Scholars and Professionals of the Fulbright Specialists Program of the U.S. Department of State's Bureau of Educational and Cultural Affairs (ECA) and the Institute of International Education's Council for International Exchange Scholars (CIES). He focuses in chemical process safety management, the integration of environmental and occupational health disciplines and public policy.

Anila Bello is a research scientist in the Department of Public Health at the University of Massachusetts Lowell. She holds a Doctor of Science (ScD) degree in Occupational and Environmental Hygiene and a Master of Science (MSc) degree in Industrial Hygiene from the University of Massachusetts Lowell, and a Bachelor of Science (BSc) degree in Industrial Chemistry. Prior to her current position she was a post-doctoral fellow in the Department of Environmental Health at the Harvard School of Public Health. Her research focuses on quantitative exposure assessment to toxic chemicals in the workplace and environment, exposure data analyses for epidemiologic investigations, exposure biomarkers, evaluation of safer alternatives to toxic chemicals, and integration of occupational health and safety with pollution prevention. Dr. Anila Bello's work includes quantitative exposure assessment to volatile organic compounds from cleaning products and evaluation of formaldehyde alternatives in histopathology laboratories. Her most recent research focuses on construction health & safety with particular interest on evaluation of exposure controls to reduce silica and dust exposures during chipping, crushing and demolition, and assessment of workplace exposures to reactive chemicals (e.g. isocyanate & epoxy resins) used for insulation and surface coatings.

Dhimiter Bello, Sc.D., MSc, is an Associate Professor in the Department of Public Health at the University of Massachusetts, Lowell, USA. He serves as associate editor for Nanotoxicology and the Annals of Occupational Hygiene. In addition, he serves in several national and international scientific committees, including ISO. He has published over 65 peer-reviewed articles and four book chapters. His research focuses broadly on exposure biology, an interdisciplinary approach that investigates quantitative and temporal relationships between environmental exposures and disease in humans. Bello's current research interests include: i) Nanotoxicology and NanoEHS; ii) Occupational skin and inhalation toxicology, particularly around reacting chemical systems, such as isocyanates and epoxies; iii) Quantitative exposure assessment for epidemiology and intervention research, primarily in high risk industries; iv) Developing methods, platforms, and tools suitable for comprehensive physicochemical and toxicological characterization of nanoparticle exposures from nano-enabled products and other emerging technologies; and v) Investigating the utility of more biologically relevant exposure and dose metrics for inhaled nanoparticles, including surface activity and oxidative stress.

Alicia McCarthy holds a B.S. in Environmental Health from the University of Massachusetts Lowell and receiving her M.S in Occupational and Environmental Hygiene in the spring of 2017. Currently, she is working as the Program Manager for Beyond Benign's Green Chemistry Commitment (GCC) higher education program, and a Research Assistant at the Toxics Use Reduction Institute (TURI) Laboratory. She is passionate about toxicology, green chemistry, and utilizing methods of prevention through substitution and elimination of hazards.

Biagio F. Giannetti has Master and DSc degree by São Paulo University (USP).Uninterruptly, he has been teaching classes since 1987. In 1992, he started his career at Paulista University (UNIP) as Associate Professor. Nowadays, he is Paulista University's Full Professor. At UNIP, he has coordinated courses of degree in engineering and currently holds the positions of Professor in the Graduate Program in Production Engineering (Master, Doctorate and Postdoctoral levels) and leader of the research activities at the Production and Environment Laboratory (LaProMA). Prof. Biagio is registered as 'Research Group Leader' in the 'Research Groups Directory' of brazilian National Council for Scientific and Technological Development (CNPq). Since 1995, he has received financial support, specially from the São Paulo Research Foundation (FAPESP). Prof. Biagio founded the International Workshop on Advances in Cleaner Production (http://www.advancesincleanerproduction.net) and Advances in Cleaner Production Network and co-founded the Paulista Cleaner Production Roundtable. He has published more than 200 academic works - including books, papers and conferences - on production and environment. His H-Index on Scopus is 18 and his i10 index on Scholar Google is 37. Prof. Biagio also is subject editor of the Journal of Environmental Accounting and Management, belongs to the scientific commitee of the Journal of Cleaner Production and is guest editor of Nova Science Publisher. Besides that, Prof. Biagio integrates the International Committee of Global Footprint Network for Standardization, is member of National Pollution Prevention Roundtable, belongs to International Society for the Advancement of Emergy Research, and is the Global Center Director of Advances in Cleaner Production Network

Cecilia M. V. B. Almeida has a Doctor in Sciences degree by São Paulo University (USP) and currently working as researcher in the group in Cleaner Production and Industrial Ecology of UNIP (Post-graduation Program in Industrial Engineering of Paulista University, São Paulo, Brazil). Member of the National Pollution Prevention Roundtable and the International Society for the Advancement of Emergy Research, she co-founded the Paulista Cleaner Production Round Table. Her research interests relate to Cleaner Production and Industrial Ecology, in which concepts , tools and techniques for the calculation of environmental and sustainability indicators are analyzed and developed. She has more than 50 peer-reviewed published papers, and acts as Executive Editor for the Journal of Cleaner Production: Cleaner Production in Latin America.

Feni Agostinho is an Agricultural Engineering with PhD in Food Engineering from State University of Campinas, Brazil, 2009. Since 2012 actuating as professor in Industrial Engineering post-graduation program at Paulista University (UNIP), São Paulo, Brazil. His subject work is related to Industrial Ecology and Cleaner Production, focusing on sustainability assessment (indicators, methodologies, theories, and modeling). He has 17 peer-reviewed published papers, 2 book-chapters, and integrates the research group of Production and Environment led by Prof. Biagio F. Giannetti. His full scientific curriculum can be seen (in Portuguese language) at http://lattes.cnpq.br/2739577358518765.

Fábio Sevegnani has a Doctor and Master in Production Engineering, post-graduation in Safety Engineering and graduation in Automation Engineering by Paulista University (UNIP). Currently working as an under graduation teacher for the Engineering courses at Paulista University. Part time researcher in the group in Cleaner Production and Industrial Ecology of UNIP (Post-graduation Program in Industrial Engineering of Paulista University, São Paulo, Brazil). His research interests relate to sustainability of urban and regional systems as well as sustainability in water and sewage treatment systems.

José Fernando Faro has a Master in Production Engineering by Paulista University (UNIP), post-graduation in Industrial Administration by Fundação Carlos Alberto Vanzolini – USP and graduation in Business Administration by Fundação Educacional Inaciana Padre Sabóia de Medeiros (UNIFEI). Quality manager in the auto-parts industry for more than 25 years currently holding Industrial Manager position. Has large experience in Administration, Production, Logistics and Quality as well as the management tools applied to quality and productivity used in the automotive industry. Actuates in the implantation of quality and environment management systems.

Johannes (Joost) Platje is a professor at WSB University in Wrocław, Poland. His research focuses on the application of new institutional economics as well as heterodox theory on issues of sustainable development. He has organized more than 20 international conferences on this topic. Prof. Platje is the president of the International Society of Intercommunication of New Ideas (ISINI), and the editor of three scientific journals (Central European Review of Economics and Management, Central and Eastern European Journal of Management and Economics, Economic and Environmental Studies).

Tino Schuette is a professor for Energy, Water and Waste Management at the University of Applied Sciences Zittau/Goerlitz, Germany. Previously, he was employed at the ENSO Energie Sachsen Ost AG, the major regional utility company in eastern Saxony, where he worked in the field of business development. He received his PhD at Dresden University of Technology, Germany in industrial economics after studying Engineering and Management at this university and the University of Wales, Great Britain with a focus on automation technology and applied microeconomics. Prof. Schuette is a member of the examination committee of the of the Saxon Energy Agency, research representative of the Faculty of Business Administration and Engineering, head of the study program Engineering and Management and a member of the jury for the Hildebrand Award of his university.

Marco Rieckmann is Professor of Higher Education Development at the University of Vechta, Germany. He holds a doctoral degree in educational research. His major research and teaching interests are: higher education, competence development and assessment, (higher) education for sustainable development, and global education. He is the President of the Commission 'Education for Sustainable Development' of the German Educational Research Association (GERA), Representative of GERA in the Council of the European Educational Research Association (EERA), and Member of the Convenors Group of the EERA Network 'Environmental and Sustainability Education Research'.

Markus Will Dipl.-Ing. (FH), works as lecturer at the University of Applied Sciences Zittau/Goerlitz. His academic interests lie in life cycle assessment, technology assessment and innovation theory. Recently, he deals with methodological questions of greenhouse gas accounting for regions. He regularly works as facilitator and consultant, trying to support the development of sustainability strategies in organizations and municipalities. Despite his deep examination with the topic, his environmental footprint is still larger as it would be adequate in a fair and sustainable world.

Javier Esquer has a B.Sc. in Industrial and Systems Engineering at the University of Sonora (UNISON), and holds a Doctor of Science degree in Cleaner Production by the University of Massachusetts-Lowell (UMass-Lowell), as well as a Sustainable Development Certificate also by UNISON. He has also authored articles in scientific publications with international recognition, and has been speaker in international events. His areas of interest include, among others, sustainable development, pollution prevention, occupational health and safety, cleaner production, sustainability management systems, energy efficiency, and education for sustainable development.

Nora Munguia is alumni of the doctoral program at the University of Massachusetts Lowell in Engineering Science with major in Cleaner Production. She is full time professor in the Department of Industrial Engineering and also serves as a researcher in the Sustainable Development Graduate Program in the University of Sonora in Mexico. Dr. Munguia is a member of the National System of Researchers and her most recent works are focused on promoting strategies to prevent, eliminate and reduce occupational hazards in the Mexican industry. Actually, she is the president of the Sustainable Engineering Academy.

David S. Zepeda is a full time professor in the Sustainability Graduate Program of the University of Sonora, México. He holds a Master degree on Sustainability. His major research and teaching interests are: Sustainable Development, Life Cycle Assessment, Sustainable Construction, Sustainable Transport Systems and Cleaner Production. He works as lecturer for the engineering division of the University of Sonora.

Arne Remmen holds a PhD in Constructive Technology Assessment by the Department of Development and Planning, Faculty of Engineering and Natural Science from the AAU. His research focus has for 25 years been on development of cleaner production and cleaner products in industries as well as on different incentives and frame conditions to support this. Eco-design and life cycle management has been tools for enterprises to incorporate environment in product innovation and to manage foreign suppliers. In recent years, the research focus has been on integrated product policy and the linkages between the instruments from minimum performance requirements (e.g RoHS and EuP) to incentives to front-runner companies via energy- and eco-labelling, green public procurement.

Romain Sacchi has a Master degree in Environmental Management and Sustainability Sciences by the Aalborg University. He works in the Department of Development and Planning at Aalborg University. His professional and academic commitment is to facilitate the development and monitoring of harmonious Economy-Environment interactions (Industrial Ecology).

CONTENTS

PREFACE

Sustainable Development Now

The concept of a sustainable world offered a significant breakthrough when it was launched during the 1980s as a guiding objective for environmentally sound global development. During that prosperous period, sustainable development became an overarching umbrella for a wide range of social and economic development programs that sought to improve human well-being within the limits of the natural resources and ecological services upon which economies and societies depend.

The concept of sustainability was included as a central commitment in the United Nation's Millennial Development Goals, and in 2015, the concept became an underlying foundation for the United Nations "universal, integrated and transformative" 2030 Agenda for Sustainable Development and the crafting of the 17 Sustainable Development Goals. Formally and globally the concept of sustainable development which had long covered resource protection, clean water and air, cleaner production, sustainable cities and consumption, clean energy and economic development was broadened to include good health, decent work, universal education, gender equality, inequality reduction and peace and justice. It is a testament to the resilience of the concept that sustainability has continued to serve as a guiding principle over these past 30 years even as the waves of history have shifted global attention from environmental protection and resource conservation to economic development and poverty reduction.

Indeed, some trends since the 1980s point towards a more sustainable world. In many countries GDP is growing and poverty rates are falling underpinned by strong economic growth in developing countries. Industrial systems are increasingly more productive and manufacturing technologies, transportation vehicles, and household products are more energy and material efficient. Cleaner production improvements among both large manufacturers and small and medium sized enterprises have reduced air contaminants, water pollution and waste generation. Renewable energy technologies now make up the fastest growing sources of energy. Ozone depleting chemicals have been largely curtailed and the global ozone layer should return to pre-1980 levels by the middle of the century. National policies and multilateral agreements have restrained the manufacture and use of some of the most highly dangerous chemicals. In many urban areas, primary air pollutants have been reduced, although some local air sheds, particularly in developing countries, remain heavily polluted. Pollution control and water treatment technologies have reduced water pollution and today, some 90 percent of the world's population has access to clean drinking water.

However, other trends are less positive. Economic growth has too often been accompanied by growing inequality and pockets of severe poverty. Even where global goals have been reached, there are wide disparities between and within countries. Malnutrition and food shortages persist. Rates of energy and material consumption continues to grow worldwide leading to regional resource depletion, ecosystem degradation, and biodiversity loss. Some 300 million hectares of forest lands have been lost since 1990. Land disposal and improper management of hazardous wastes remains a significant problem. Climate change is now a reality and its effects can be felt in increasing global temperatures, warming oceans and rising sea levels, increasing ocean acidification, retreating glaciers and decreasing Arctic sea ice, turbulent weather patterns and new droughts and weather-related disasters. Urbanization continues with over half of the world's population now living in cities, including some 21 megacities of over 10 million people, where massive slums continue to house the most vulnerable.

However, such trends only tell a portion of the story. Environmental impacts may be documented and measured, but the concepts of economic and social development are more difficult to assess. In part, this is a problem of measurement and in part a problem of goal definition.

The United Nations has championed the measuring of ecosystem and atmospheric responses to unprecedented levels of material production and consumption and the ecological footprint of some 7 billion (soon to be 9 billion) people through assessments such as the Global Environmental Outlook, the Global Chemicals Outlook and the Global Waste Management Outlook. However, these assessments rely on found data. Inventories and projections can only be based on the data that is at hand and large gaps exist for global data on changing land patterns, wetlands and forest conditions, ocean and marine systems and most species populations. While large amounts of data exist on economic and social indicators, there remains much concern that the indicators do not represent the felt conditions of people and communities. Measuring GDP has been roundly criticized as missing much that makes up economic security and material prosperity. Focusing on national or regional indicators of economic growth, employment and wages has been challenged as a means of assessing the perceived value of goods and services, particularly where inequality is ramped. Measuring demographic conditions, education levels, and social service utilization does not well represent social satisfaction. Economic and social conditions are complex and indicators and measures are needed that more directly address the felt side of well-being.

The goals of development are also muddled. The idea of development, like the concept of progress, is founded on values about the composition of human well-being and these are largely values put forth by those in wealthy, "modern", and technologically advanced countries. These values support high-energy, consumption-oriented economies and minimize questions about who benefits from such development and whether inequality is endemic to such societies. Such values support globalization and free trade and inadvertently advance the homogenization of local and regional cultures. Certain assumptions about technological and economic structures are "locked in" by historical trends and past investments and by the heavy hands of those who currently benefit. Recent experiences of electorates in both developed and developing counties suggest just how unacceptable such values may be to some and beg for a more inclusive way to shape the goals of development. The idea that the definition and objectives of economic and social development might best be drafted by, or at least informed by, the active participation of those whose communities are to be developed is recent, but it opens new opportunities for considering sustainability in a more inclusive and diverse context.

Opening up the participation of those in developing economies in defining the goals and shaping the means of promoting development raises issues around fairness as resources are not equally shared and the costs of development and environmental degradation weigh heaviest on the poor. And justice becomes central not only for the future, but also about the past. The heavy focus on the future underlying sustainable development can try to ignore the pain and anger of communities where a legacy of resentment runs deep, but a sustainable world cannot be achieved without a shared sense of justice and acceptance and at least some commitment to peacefulness and non-violent conflict resolution.

Sustainable development places a high value on development as a means for improving the quality of human life, but the environment is often treated as a material residual to be protected for sure, but left without its own goals. Goals may be set to restrain degradation, work within planetary boundaries or restore desired resources such as forests or fisheries. However, so much of the planet's lands, waters and ecological systems have been degraded that simple protection is hardly enough to guarantee a future of healthy natural systems. Some argue for a restorative or regenerative approach that sets goals for environmental well-being and supports programs to re-build, re-energize and re-construct natural systems that are healthy, robust and resilient. Embracing the environment's own systems of "development" may be the best way to assure the prospects for future generations.

Today, as a new global focus is emerging that embeds environmental protection deeply into economic and social development, sustainability must again readapt to the changing times. What lies ahead offers a wide range of new challenges. Population will continue to increase with the largest increases occurring in the developing economies and among the world's elderly. It will be increasingly costly to find new sources of fresh water, mineral deposits and arable lands. New technologies such as nanotechnology, synthetic biology, genetic engineering, artificial intelligence, robotics and the Internet will continue to challenge the way that we live, work, play, communicate and make war. The global fiscal crisis on the past decade and the increasing retrenchment of multilateral aid have reduced funding for developing economies and restrained risk taking among major business institutions. And new social problems are emerging, such as a rising tide of nationalism and terrorism, increasing skepticism about globalization, and mass migrations of climate and war refugees.

Can sustainability continue to be the overarching guiding principle for a future of such changes? The varied stories in this collection suggest the many possibilities, and, even more than grand, global pronouncements, it is stories like these that point out what people on the ground can do to achieve a sustainable society on this planet.

The United Nations Sustainable Development Goals set out an ambitious mission for the next 20 years, but these worthy objectives are designed upon the values and governance structures of today. Some of what lies ahead will continue as trends from the past, but the story of human life is evolving and we are always limited in our predictions by what is discontinuous and unpredictable. The concept of sustainability has stood us well over these past decades. It will take a lot of work and good governance to assure that this overarching principle continues to serve us as an effective guide for the uncertainties and challenges of the future.

Kenneth Geiser, Ph.D.

Professor Emeritus, University of Massachusetts Lowell

INTRODUCTION

In accordance with the Brundtland Report, sustainable development is development that meets the needs of present generations without compromising the ability of future generations to meet their own needs. There are three fundamental dimensions of sustainable development: environmental, social, and economic. In theory, the three dimensions must maintain a balance; however, with the many uncertainties of the current worldwide economic outlook, maintaining a balance between these dimensions will be more difficult to achieve than before, and the environment is likely to become the first victim.

All treaties that involve sustainability acknowledge that there are several ways to promote sustainability. In this context, the purpose of this book is to increase the involvement of students in sustainability initiatives at both the bachelor and graduate levels by educating students about successful or unsuccessful sustainability efforts around the world. In this book, eight international experiences are discussed that present successful approaches in implementing sustainability projects.

The first chapter focuses on industrial ecology as a tool used to achieve sustainable development, and it includes examples from The Netherlands and Sweden. Both cases are based on industrial ecology initiatives by industry; however, the case from The Netherlands is based on the planning phase of industrial ecology, while the case in Sweden is based on uncovering industrial ecology.

The second chapter discusses the relation between sustainable industrial production in the United States and the primary prevention of environmental and occupational disasters as a threshold activity to achieve sustainability. An effective strategy that is utilized for the prevention of major chemical accidents is evaluated using a system approach. The chapter argues that the prevention of an environmental or occupational catastrophe is fundamental to sustainable industrial production.

The third chapter fosters the case of Sustainable Construction. In particular, the chapter shows the environmental impact and health risks associated with the use of spray polyurethane foam. Spray foam insulation is a good example of a high quality-insulating product that relies on isocyanates, one of the most potent chemical sensitizers known to man. While SPF can be used safely, its history of the past few decades illustrates the various challenges in maintaining a balance between product formulation and performance, raw material input and occupational health issues arising during its application. These aspects of product development and stewardship are important considerations in the sustainability efforts and require continuous attention, especially when new applications and or formulations enter the marketplace.

The fourth chapter describes cleaner production practices in the Brazilian industries. The aim of this chapter is to present the experiences of a medium-size metal-finishing company that implemented Cleaner Production (CP) programs to improve processes and resource use as well as to evaluate the results of the changes in a joint action with the researchers of Paulista University.

The fifth chapter presents the economic principles used to assess the efficiency improvements for sustainable development. The world has become increasingly complex due to technological advances and increasing trade on a global scale, among other factors. Consequently, efficiency improvements for sustainable development may lead to various fragilities and increased unsustainability.

In the sixth chapter, the role of higher education in sustainable development and the opportunities of service-learning in this context are discussed. In addition to other competence-based teaching and learning approaches, service-learning offers several rich learning opportunities for students. The chapter describes the case of service-learning courses at the University of Vechta, Germany.

The seventh chapter reflects on the existence of true sustainability. In this chapter, it is stated that the business model of an authentically sustainable company focuses on "doing business, doing good" while creating a social and environmental value. Cases of successful companies that earned profits by embracing sustainability and contributing to society and the environment are discussed.

The eighth chapter argues that energy efficiency is a key strategy for achieving sustainability. In this context, the cases of General Purpose Technologies (GPT) are described, particularly illumination, compressed air systems, and electromechanical drives, in small, medium, and large-scale enterprises.

The ninth chapter presents a general overview of an LCA case conducted in Mexico for automobile exhaust manufacturing as a practical experience of the Sustainability Graduate Program of the University of Sonora. The results show that the overall impact of the company was low during hot-end sub-assembly production in contrast to the material extraction stage.

Finally, the tenth chapter examines the development of industrial symbiosis through a practical model for physical, organizational, and social interactions in six different cases from around the world. The results provide a framework that can be used by industrial symbiosis practitioners to facilitate the creation of synergy in industrial areas.

In the year 2017, the outlook is not encouraging for advocates of sustainability issues. Recent financial and political developments suggest that there will be little support for sustainability initiatives. Fortunately, Albert Einstein argued that a crisis can be beneficial for society because it can lead to progress, and this is the opportune moment in which sustainability promoters must collaborate to save the planet.

The book International Sustainability Stories: Enhancing Good Practices is aimed at enhancing student involvement, in both bachelor and graduate level, in sustainability initiatives by telling them successfully, or not so successfully, efforts around the world. This was written by senior academics and scientists with practical experience in promoting sustainability initiatives. In their efforts to achieve sustainability, they accumulated a wealth of knowledge, successes, and failures, which makes them worthy of admiration.

I feel honored to have coordinated this effort, and I am fully confident that during the post-2015 era, society will successfully achieve the objectives of the Sustainable Development of the United Nations Organization. This will result from the commitment that millions of people who strive to accomplish this goal have made to this planet.

I thank each author and all who contributed to their success in the preparation and publication of this work.

Luis Velazquez
Coordinator

1. INDUSTRIAL ECOLOGY: EXAMPLES FROM THE NETHERLANDS AND SWEDEN

Leenard Baas

1. Introduction

In one of the first definitions of industrial ecology, Frosch and Gallopoulos (1989) described it as a concept wherein "the consumption of energy and materials is optimized, waste generation minimized, and the effluents of one process serve as the raw materials of another process." New approaches, such as industrial ecology, are designed to substitute routine approaches. For example, the concept of cleaner production was designed to be an approach to pollution control management; however, the routines of existing managing concepts often hamper the implementation of new concepts. As a result, despite promising business models—or even generating better business models—new concepts tend to be applied marginally. According to Baas (2005), there are two main pathways in developing industrial ecology activities: the organization of those activities and the activities that are being aspired to. As market incentives are important drivers for industry, the involvement of industry representatives is required. That can be different for existing industrial sites (brown field) and newly designed industrial sites (green field).

The concept of industrial ecology emerged in the 1990s. Industrial ecology has been worked out in the Kalundborg industrial park in Denmark as industrial symbiosis, which refers to the bi-lateral links that exist between industries. The examples of industrial ecology/symbiosis presented in this chapter will illustrate the eco-industrial relationships in The Netherlands and Sweden. The case of The Netherlands is based on the planning phase of industrial ecology, while the case in Sweden is based on uncovering industrial ecology. The discussion about planning or uncovering industrial symbiosis is described in detail by Chertow (2007).

Both cases involve industrial ecology initiatives by companies. Whether industrial ecology is better applied through the initiatives of industries or through governments depends on the societal context. It has been observed that the success of the eco-industrial park initiatives though the government is best in China, while the success of the eco-industrial park initiatives through industries is better in Northern industries.

2. Characteristics of Industrial Ecology

Industrial ecology and symbiosis can be characterized in different ways. The concept can be approached on a policy (national, regional, and/or municipal), operational (links between companies), and/or industrial park level (eco-industrial parks). Within these levels, there are various issues and dimensions.

Table 1.1 Typology of issues and dimensions of an industrial ecology framework

Issues and dimensions	Content
Target	Zero emission: cleaner production, closing all loops, no leaks
Policy	Policy development: the recognition and acknowledgement of potential
Holistic industrial ecology concept	Decarbonization: evolution of the energy system Dematerialization: fulfilling more needs with less stuff and less energy Material substitution: the reduction of the environmental burden and toxic use throughout the production, use, and after-life management of all products Service for product (functionality economy): provision of product-service combinations that require less total material and energy from a life cycle perspective
Organization	Intermediary organization: organizing activities that go beyond the scope or purview of individual companies; the development of a consensus-based regional 'industrial ecology covenant' Exchange system: interactive information system Public/private partnership: infrastructure
Means	LCA: an industrial ecology quick scan method development, testing, and adaptation to the industrial ecology context Materials flow and balance analysis: comprehensive accounting for industrial ecosystems at several levels (firm, sector, region) by elements (Cadmium, Chlorine) and by sectors (wood)
Material activities	Utility-sharing: compressed-air, energy, and steam systems Cascade: systems for water, waste, and energy cascading Joint treatment: of bio-sludge, waste, and wastewater Resource delivery: the production of basic compounds for the region
Non-material activities	Education: general in the area and specific on industrial ecology Labor: a flexible pool on industrial ecology development Transport: joint use for employee mobility and goods transport
Implementation	Test: sustainability basis Trust: good-will and competence trust
Monitoring	Indicators: intensity of use, waste/product ratio, improvement in the quality of life sustainability index of the region
Evaluation	Reflection: reporting, feedback, and on-going support to ensure the long-term future of the regional sustainable development goals and objectives

Source: Baas (2005)

3. Waste heat application in the Rotterdam Harbor and Industry Complex

In 1994, the regional industry association, Deltalinqs, decided to implement an industrial ecology research program in the Rotterdam Harbor and Industry Complex called the Industrial Symbiosis Program (INdustrial Eco System – INES programme 1994-1997). Research teams from Delft University of Technology and Erasmus University Rotterdam were asked to undertake this research (Baas, 2005). Fifteen projects in total were defined based on the information provided during a two-day industrial ecology workshop in which a confidential questionnaire was administered to companies (Baas, 2005).

One of the projects in the Rotterdam Harbor and Industry Complex was concerned with the issue of waste heat and CO_2. Companies that were emitting waste heat and CO_2 into the air and/or surface water and neighboring companies that were producing heat necessary for their production processes attended the meeting. The need for an "open door" proposal mechanism and project design for connecting these industrial systems was identified; however, the project that was eventually selected, which involved sharing waste heat, actually laid the foundation for the emergence of strong (political) attention. At the end of the INES program, the industrial association and an energy distributor jointly discussed the best ways to utilize approximately 2200 megawatts of waste heat that was emitted into the air and approximately 3000 megawatts that was emitted into the water. The initial option identified for further study was a pipeline system that would be used to connect the suppliers and buyers in the industrial region. It was calculated that such a pipeline system would cost € 112,700,000 and would require government funding for a new infrastructure that would distribute this new source of energy to the industrial region. This waste heat project was further explored in the follow-up INES Mainport Project from 1999-2002 (Baas, 2005).

After it was determined that the establishment of a pipeline infrastructure for the entire area was uneconomic, smaller scale projects were initiated in the INES Mainport Project. The Utilization of Industrial Rest Warmth Project involved eight partner projects in the Botlek and Pernis industry clusters. The estimated total investment required was € 83.6 million. The Dutch National Project Office for CO_2 reduction plans was requested to provide a 30% subsidy in March 1998. A 27% subsidy was secured in November 1998. A partnership of seven Deltalinqs companies tested the technical, operational, and economic feasibility of the eight partners' projects in 1999. Three projects were cancelled due to poor results. Of the five remaining projects, four were rejected, three for economic reasons and one on the grounds of discontinuity of supply (see Table 1.2; Baas, 2005).

Table 1.2 Waste heat supply sub-projects and the reasons for their rejections

Waste heat supply project from	Reason for rejection
Air Products to Shell Chemistry	Economic: pay-back time is longer than 30 years
AVR to Dapemo	Discontinuity in steam demand of Dapemo
Lyondell to Climax	Economic: not feasible
Esso to ORC	Economic: not feasible

Source: Baas (2005)

The four projects represented 63% of the estimated investments for the total of eight projects. This also meant that 63% of the subsidy was rejected. One large remaining project was cancelled due to the closure of the main partner, the Kemira Agro plant, which also meant that the pathway of smaller clusters for waste heat supply was not an option.

Initially, despite the enormous waste heat surplus, nearly all large plant managers shared concerns for economic (the costs of the required infrastructure) or strategic (the perceived loss of independence) reasons. These concerns were the main reasons that during the period from 1997 – 2001, the waste heat supply project had to be downsized from a holistic regional approach to several smaller cluster projects. After the large-scale approach appeared to be economically unsuccessful, a feasibility study for heat delivery through a private "Heat Company" was performed (ROM-Rijnmond, 2003). One of the drivers for the continuing efforts to implement this project was pressure from the Water Management Authority, which made it clear that it would no longer accept additional emissions of heat into surface waters.

Industry management has always viewed environmental investments as efficiency improvements with an expected return on investment of two to three years (Baas, 1998). When environmental policies became better integrated into general industry policies, an expected return on investment of six years became commonplace. With the liberalization of the public energy facilities, such as electricity and natural gas (Jong, 2006), in the Netherlands around the turn of the 21st century, the situation reversed. The privatized energy companies began to expect a lower rate of return on their investments than industries, although not as low as the traditional rate of return that was expected when they were acting as public energy companies[1]. As a result, the differences in the "acceptable" investment time frame between industry and energy companies hindered industrial ecology initiatives in the Rijnmond (broader Rotterdam) area.

Following the completion of the INES Mainport Program and in cooperation with the ROM-Rijnmond Energy projects (a joint industry-government program), several new partners entered the "playing field," including housing cooperations and energy suppliers. They agreed to pursue the project on the conditions that the decoupling of the waste industrial heat of the Shell Pernis Refinery (and later of Esso/Exxon and BP refineries) to the Rotterdam city district heating system was economically viable and that the responsibility for the coupling between industries and cities should be clearly organized. In 2002, the Rotterdam municipality began to provide a guarantee for

1 Some experts have stated that in the decision-making process for the unification of the European Union market, for which obstacles to the optimal operation of the free market had to be removed, it was forgotten that from an economic perspective, the free market does not always provide the best solution. Sometimes a monopoly works better, such as in the case of electricity supply. This is because with natural monopolies, owners must have long-term investment perspectives.

the extra funds for a temporary heating system in a new residential area near the Shell industrial site in Rotterdam. It also installed a financial safety net for the construction phase if the waste heat project should fail. The application of waste heat was intended to serve as a substitute for the natural gas supply in the Rotterdam area.

When all conditions for realization were finally met in 2004 (including the liberalization of the Dutch energy market and reductions of CO_2 demanded by the national government as part of the Kyoto-protocol agreement), the planned recovery of Shell's 6 MW of waste industrial heat as a supply for the city's district heating system would make the temporary equipment redundant, as 3,000 houses would benefit in the Hoogvliet residential area; however, Shell withdrew from the project in 2007, and new arrangements had to be explored. After a delay of several years, new initiatives were adopted for the district heating system project in 2012. The heat supply system is still intended to provide 100 MW to 50,000 houses and the greenhouse sector (ROM-Rijnmond, 2005). In addition, future activities are planned to connect 500,000 houses and companies in the Southern part of the province of Zuid-Holland in 2020 (ROM-Rijnmond, 2006).

CO_2 recovery is also included as part of the project. A new private company, OCAP, has ownership of the infrastructure and the responsibility to capture CO_2 emissions from the Shell plant (in Pernis) and to distribute the waste emissions to 500 greenhouse companies to the north of Rotterdam. The CO_2 delivery project (as a substitution for the combustion of natural gas) began in July 2005. In 2007, the greenhouse companies achieved a reduction of 170,000 tons of CO_2 emissions by avoiding the burning of 95 million m^3 natural gas[2]. The designed future waste heat infrastructure is shown in Figure 1.1 (the red lines are the primary new pipelines as common carriers, the blue lines existing pipelines in a district heating system, and the dotted red lines are to be constructed in a later phase)[3]. The factory examples include refineries, power stations, and incinerators that will function as heat hubs within the district heating system. The district heating system will supply Rotterdam (1) and its surrounding areas (6), Dordrecht/Zwijndrecht (2), the greenhouse area Tinte/Vierpolders (3), the city of The Hague and its surrounding areas (4), and Delft (5).

2 Natural gas is burned in greenhouses for heating and the input of CO_2.

3 The picture of the Botlek Loop at the left under part of Figure 1.1 illustrates the waste heat exchange between companies, houses, greenhouses, and an underground storage center for cold and heat supply in the Botlek industry area.

Figure 1.1 Future Waste Heat Infrastructure
Source: Baas (2005)

There have been several highs and lows in the decision-making processes concerning the application of waste heat in a district heating system for the city of Rotterdam and its surroundings. In February 2011, the municipality of Rotterdam and E.ON began a joint venture for a new "Heat Company" for waste heat application. While the significant waste heat emissions cannot be ignored, projects cannot proceed if they are uneconomic.

A major lesson learned from the INES program in the Rotterdam Harbor and Industry Complex was the spontaneous spin-off of initiatives that were inspired by information and the dissemination of results. New activities were observed, ranging from connecting waste heat from a chemical company to a neighboring truck cleaning company, the privately initiated and constructed "Happy Shrimp Farm" (a king-size shrimp breeding greenhouse water basin utilising CO_2, NOx, and waste heat from a power plant), the IS design of a new chemical plant, and a new industrial site, Maasvlakte2, which was reclaimed from the North Sea and was designed following IS principles (Baas, 2008).

4. State-of-the-art Industrial Symbiosis in Sweden

In this section, the Swedish forest industry and the biomass links in Sweden are used as examples of unplanned industrial symbiosis links (Baas, 2011). Nature conservation has a long history in Sweden, as illustrated by the more than hundred-year-old slogan "Nature is everyone's." Production-oriented forest policies have dominated since the early 20th century and have explored cascade flow management and industrial symbiosis under the label of integrated diversification for efficient resource use; however, in the 1960s and 1970s, many companies became too diversified despite creating more value (Hill and Jones, 2001). As a result, in the 1990s, the argument for changing the strategies of many larger corporations to focus on a limited number of forest products seems to have been influenced by globalization trends as well as the needs for decreasing bureaucracy and higher coordination costs. Nevertheless, Wolf and Petersson (2007) found that more than a third of the companies investigated in the Swedish forest industry had some type of material or energy exchange with adjacent entities, such as is demonstrated in the Mönsterås network. Although this network is outside of the regions compared in this chapter, the academic study is illustrative for the forestry industry network in Kisa, Östergötland.

In Mönsterås, the pulp mill and pellet production plant are co-located, and they share buildings and personnel and exchange materials and energy. The pulp mill delivers steam and electricity to the saw mill, steam, electricity, and bark for pellet production, and waste heat to the local district municipal heating system. In turn, the sawmill delivers saw sawdust and wood chips to the pulp mill (Wolf, 2007, see Figure 1.2).

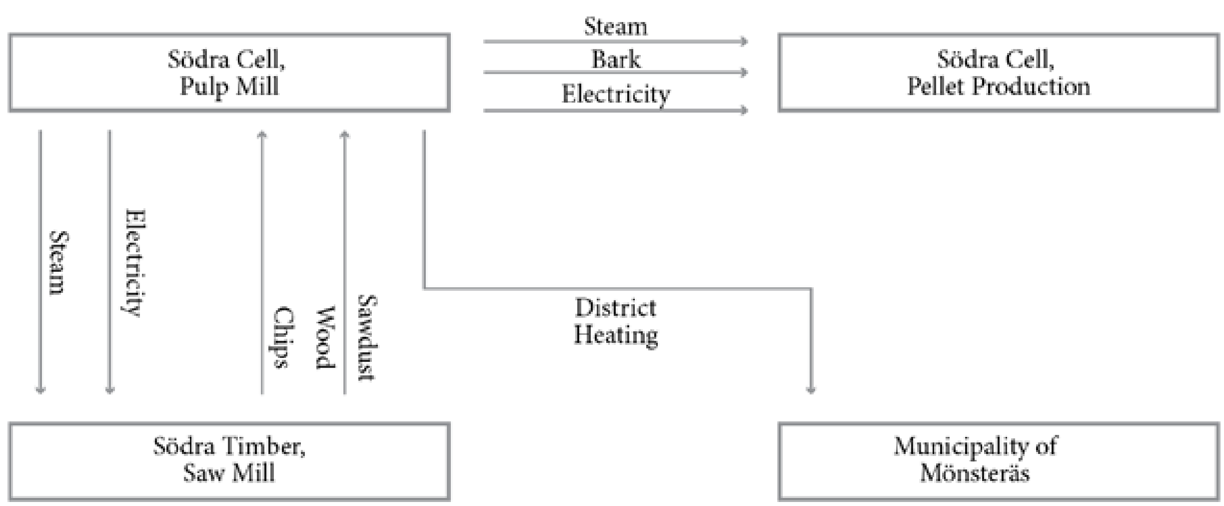


Figure 1.2 Mönsterås Forest Industry's By-Product Network
Source: Wolf (2007)

Another spontaneous development was observed in the Östergötland region in which Cleantech Östergötland, which is an organization that comprises the municipalities of Linköping and Norrköping and one-hundred industrial organizations and promotes the region's business, was established in 2008. This organization "marketed" the IS concept as an umbrella for environmentally driven regional development in Östergötland and defined it as "business practice": "…characteristic for industrial ecology is to turn environmental problems into business opportunities by applying wide system boundaries, using resources efficiently and co-operate through resource sharing" (Cleantech Magazine, 2009).

Several IS activities were developed prior to the establishment of Cleantech Östergötland, such as a 1.7 kilometer pipeline for the utilization of nutrient-rich waste water from a slaughterhouse into the biogas production facility in Linköping. Cleantech Östergötland promotes these types of activities as business cases. Likewise, district heating companies, such as Tekniska Verken in Linköping and E.ON in Norrköping, used IS as a driver of regional sustainability innovation. For example, biogas production, as affiliated or linked facilities of the district heating companies, provided biogas for all public bus transport and taxis in both cities. The local governments used this substitution decision as a means for solving the increasing city center environmental pollution caused by traditional fuel-driven transport. Due to the 5% average biofuel addition to the petrol use in Sweden and the 5% pure biogas use in Östergötland, approximately 10% of transport in Östergötland relied on biofuel in 2009. As an example of the many biomass symbiosis links in Östergötland, IS in the Händelö region is illustrated in Figure 1.3 (Martin, 2010).

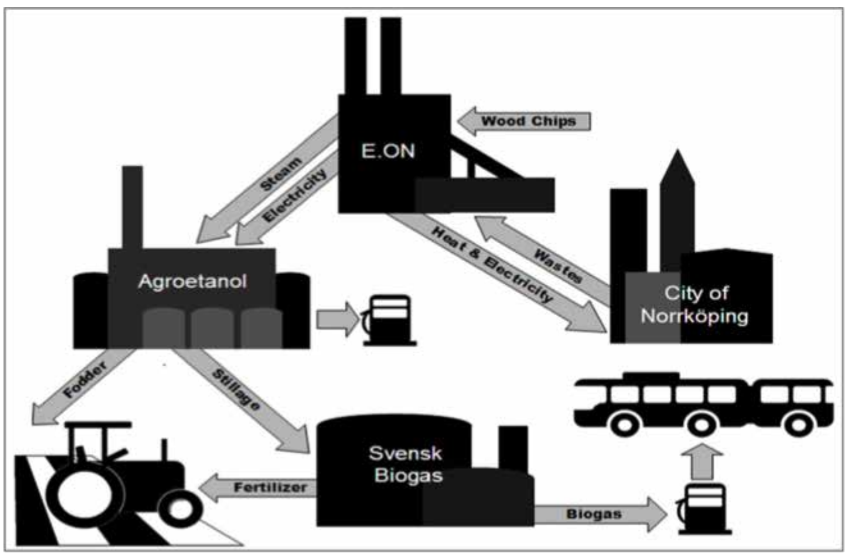


Figure 1.3 Industrial Symbiosis Network in the Händelö Industry Region
Source: Martin (2010)

The Handelö industry area in the Norrköping municipality is interesting: it combines an IS renewable energy cluster, a logistical center, and Natura 2000 conservation[4] areas (Nicklasson, 2007). All links were developed step-by-step. Currently, the IS renewable energy cluster links the E.ON combined heat and power (CHP) plant with a biogas plant and an ethanol plant. The E.ON plant has a fuel mix of 95% renewable resources, including household waste, rub-

4 Natura 2000 is the name of the EU network of protected nature areas.

ber, woodchips, and wood waste. The biogas plant owned by the CHP plant produces biogas from sludge derived from Norrköping's waste water treatment facility. After fermentation, the biogas is upgraded to vehicle fuel and distributed to local refuelling stations. The CHP plant delivers 29% of its output as steam to the ethanol plant. The ethanol plant uses wheat, triticale, and barley as raw materials for the annual production of 210 million liters of bioethanol and 195,000 tons of protein pellets for livestock feed. The remaining part of the sediment that is not used for livestock fodder becomes raw materials for another biogas plant.

Several IS links in Sweden have been developed based on a single business case. Planned IS activities in a larger industrial park format are rare (the next example of the Landskrona Industrial Park is outside of Östergötland) and seem to be difficult to manage in Sweden. The Landskrona IS Project was "created" by Lund University as part of Ph.D. research (Mirata, 2005). The "creation" approach of the IS Landskrona Project for networks was based on the following definition: "a collection of long-term, symbiotic relationships between and among regional activities involving physical exchanges or materials and energy carriers as well as the exchange of knowledge, human or technical resources, concurrently providing environmental and competitive benefits" (Mirata and Tareq, 2005).

The involvement of anchor organizations and key personnel in the field produces important drivers for the dissemination of IS activities within a region. It is important to identify them as "owners" of the project when the project is initiated from the outside. Unfortunately, for the Landskrona Project, the IS initiative was phased out when the research project budget, including external IS management, ended in 2006. Although the Landskrona industrial park led the introduction and dissemination of cleaner production in Europe between 1987 and 1989, the industrial ecology concept did not generate a similar spin-off (Mirata, 2005).

In addition to the academic discovery of renewable energy and efficient material use based on industrial symbiosis (Wolf et al., 2005), new IS approaches recently began in Östergötland. A four-year Sustainable Norrköping Program (2010-2013) has investigated the IS development of an energy cluster and a logistics center in the Händelö industrial area. A visualization center for the popular science communication of industrial symbiosis through the visualization of material flows and connections in the Händelö area is also part of this project. It is argued that the citizens' willingness, commitment, and support for these changes are critical dimensions for further developments. In other words, their empowerment, continuing engagement, and support are essential to ensure that this region continues its transition path.

In another example, the Linköping district heating company, Tekniska Verken, and Linköping University agreed to fund a 10-year Industrial Ecology Research Program with Tekniska Verken connected to a new chair of industrial ecology (www.iei.liu.se/envtech). For the Industrial Ecology Research Program, industrial symbiosis is defined as follows: *"industrial symbiosis is seen as a process whereby materials, water, energy and informational flows between and among companies are investigated with the objective of developing and improving co-operative links between/among them*" (Baas, 2011). The long-term Industrial Ecology Research Program from 2009 – 2019 will contribute to focused research, education, and knowledge dissemination related to clean technology, industrial symbiosis, waste to energy, and biofuel applications on a sound economic basis through the results of Ph.D. research and continuous evaluations of sustainability projects in practice.

Research projects that focus on the utilization of waste heat, CO_2, and nutrients from district heating company in greenhouses, biofuel synergies, landfill, and urban mining began in 2010.

It is remarkable and encouraging that the policies and activities developed in Östergötland have already resulted in more than a 20% CO_2 reduction compared with the level of emissions in the region in the 1990s. District heating systems and biofuel applications appear to be basic elements in the emergence of a "silent" transition to a "100% renewable energy" region.

5. Conclusion

Both the planned IS in the Rotterdam Harbor and Industry Complex and the uncovered IS in Sweden provided large IS connections in industrial regions. A district heating system was often the basis for IS connections in Sweden, while the refineries and energy suppliers provided the basis for IS connections in the Rotterdam area. The examples in this chapter illustrate the most general applications of industrial ecology/symbiosis.

References

Baas, L. 2005. Cleaner Production and Industrial Ecology; Dynamic Aspects of the Introduction and Dissemination of New Concepts in Industrial Practice. Delft: Eburon

Baas, L.W. 2008. Industrial Symbiosis in the Rotterdam Harbour and Industry Complex: Reflection on the interconnection between the techno-sphere and the social system. Business Strategy and Environment. 17: 330-340

Baas, L. 2011. Planning and Uncovering Industrial Symbiosis: Comparing the Rotterdam and Östergötland regions. Business Strategy and Environment. 20(5): 428 - 440, DOI: 10.1002/bse.735

Chertow, M. 2007. Uncovering Industrial Symbiosis. Journal of Industrial Ecology. 11(1): 11-30

Cleantech Magazine. 2009. Environmental Technology in the Twin Cities of Sweden. Marknadsbolaget Fjärde Storstadsregionen and Regionförbundet Östsam: Linköping

Frosch, R.A., Galladopoulos, N. 1989. Strategies for Manufacturing. Scientific American. 261(3): 144-152

Hill, C.W.L., Jones, G.R. 2001. Strategic Management: An Integrated Approach. Boston: 5th ed.

Jong J. de. 2006. Liberalising Dutch Energy Markets; Champions and governance, rules and regulations: The 1995 – 2005 stories. Clingendael International Energy: The Hague

Martin M. 2010. Industrial symbiosis for the development of biofuel production, Licentiate Thesis No. 1441. Linköping Studies in Science and Technology, LIU-TEK-LIC-2010:12

Mirata M. 2005. Industrial Symbiosis - A Tool for More Sustainable Regions? Ph.D. IIIEE, Internationella miljöinstitutet, University of Lund: Lund

Mirata M, Tareq, E. 2005. Industrial symbiosis networks and the contribution to environmental innovation: The case of the Landskrona industrial symbiosis programme. Journal of Cleaner Production. 13: 993-1002

Nicklasson, D. 2007. Industriell Ekologi som Utgångspunkt för Utveckling och Marknadsföring av Näringslivet i Norrköpings Kommun [Industrial Ecology for Development and Marketing of Trade and Industry in Norrköping]. M.Sc. thesis, Linköping University, LIU-IEI-TEK-A-07/00259-SE (in Swedish with English abstract)

ROM-Rijnmond. 2003. To C or not to C, Rotterdam

ROM-Rijnmond. 2005. Rijnmondse Routes, Rotterdam

ROM-Rijnmond. 2006. Grand Design; Warmte voor Zuidvleugel Randstad (Heat for the Southern part of Zuid-Holland). Rotterdam

Wolf, A. 2007. Industrial Symbiosis in the Swedish Forest Industry. Ph.D. thesis Linköping University. Linköping

Wolf A., Eklund M., Söderström M. 2005. Towards cooperation in industrial symbiosis: considering the importance of the human dimension. Progress in Industrial Ecology; An International Journal. 2: 185-199

Wolf, A., Petersson, K. 2007. Industrial symbiosis in the Swedish forest industry. Progress in Industrial Ecology; An International Journal. 4(5): 348-362 www.iei.liu.se/envtech, assessed January 2010

2. CATASTROPHE PREVENTION AS SUSTAINABILITY: SYSTEMS APPROACH AND PROCESS SAFETY PERFORMANCE INDICATORS IN INVESTIGATIONS OF MAJOR ENVIRONMENTAL DISASTERS

Rafael Moure-Eraso

1. Introduction

Sustainable industrial production is a human-made, goal-oriented system that serves humanity's needs to produce goods and services without causing irreparable damage to the human or physical environment. The consequences of breakdowns in the sustainability of industrial production involve negative impacts on the human and general environment. The most dramatic of these impacts include catastrophic fires, explosions, and chemical spills from complex and extensive industrial processes. There are two major examples of these catastrophes: the accidental release of Methyl Isocyanate gas from a Union Carbide pesticide plant in Bhopal, India, in December 1984, which resulted in at least 4000 deaths and 200,000 injuries (Perrow, 1999), and the fire and explosion of a British Petroleum off-shore Macondo-Deepwater Horizon crude oil platform, Gulf Coast, USA, in 2010, which caused 11 fatalities, 17 critical injuries, and a spill of approximately five million barrels of crude oil in the Gulf of Mexico US (National Commission, 2011). The stakes of these systemic failures are high indeed, creating an imperative need to develop a structure of analysis to determine the root causes of these catastrophes to prevent them.

This chapter demonstrates that the investigative process of environmental disasters using the system approach is an effective strategy in the prevention of these tragedies. This is a fundamental first step in attaining sustainability and ensuring the viability of sustainable industrial production that does not harm workers or communities engaged in the production of goods and services. Catastrophic mishaps deny the very possibility of industrial production by the physical destruction of the industrial site, let alone its sustainability. Management science has suggested a system of "social accounting" of human enterprises by developing a set of comprehensive indicators to establish what is known about progress toward general, acceptable goals (Van Grigch, 1971). If the goal of an industrial enterprise is sustainability—with environmental and occupational sound practices—a set of appropriate quantifiable indicators could be developed to measure success in the prevention of serious breakdowns that lead to a possible collapse of the enterprise, which in turn would lead to dire consequences for the environment.

A case study of the investigation of a fire, explosion, and massive oil spill at the offshore platform of BP in the Gulf of Mexico in April 2010, which was conducted by the U.S. Chemical Safety and Hazard Investigation Board (CSB), will serve as an example that can be used to identify good practices for prevention. A system approach of an analysis of the incident is presented using safety process indicators to diagnose the abnormal functioning of a system that drastically failed and therefore halted the process of crude oil production in an offshore operation and caused dire environmental consequences.

2. System Approach

In the early 1970s, a general system theory was developed that defined a system approach to analyze human enterprises. It was presented as a new type of scientific method that could manage complex systems and could integrate concepts such as adaptation, learning, motivation, evolution, and their interactions with all factors governing industrial production, including its sustainability. It includes the paradigm of the traditional scientific method with new approaches for the measurement, explanation, validation, and testing of performance indicators. It also integrates the social sciences (so-called soft variables) with new ways to engage with analyses of the design and improvement of human enterprises. This new approach connects the physical sciences with social, behavioral, and life variables, such as values, judgment, beliefs, and sentiments (Van Grigch, 1971, 2000). The system approach (SA), expressed as the careful development of performance indicators, is a new investigative process that can be applied to the design and improvement of organizations engaged in industrial production. The SA incorporates behavioral and strictly mechanistic views and examines organizations as an integrated whole whose goal is to achieve overall system effectiveness while harmonizing the potential conflictive objectives of its components (Van Grigch, 1971, 2000).

Investigating major accidents in industrial settings requires that the practitioner be able to diagnose the abnormal functioning of a system that impedes the realization of sustainable production. Therefore, the prevention of major accidents must be part of the design of the production system. Using the SA theory, it is possible to improve industrial processes by using safety performance indicators (quantitative and qualitative). The definition and analysis of such indicators could then be incorporated into the management of enterprises by using them as predictive tools to validate prevention strategies. Regarding safety, these indicators must include both measurements of concrete critical activities, such as "response time during near misses," and measurements of social indicators, such as "worker participation," on safety decisions.

3. Process Safety Performance Indicators

In the Petrochemical industry, safety indicators are quantitative measurement techniques that drive process safety performance improvement and training. The indicators should be relatively easy to understand by all parties affected and relatively easy to implement in an industrial setting. An accepted set of safety indicators should be suitable for benchmarking safety performance to observe trends to help prevent safety failures that could become catastrophes as well as to initiate programs of evaluation and continuous improvement.

In general, the indicators should be consistently defined and should be able to be compared between processes and industries for statistically validity.

4. Lagging Indicators – Reactive Monitoring

Historically, the first safety indicators chosen by industries as gauges of safety performance measured several actual human and material losses after incidents occurred. They are known as "lagging indicators" due to their retrospective character; they only suggest corrective or preventive interventions as a reaction after industrial accidents have already occurred (Baker, 2007). Safety experts generally agree that these are some examples of lagging indicators:

- Worker fatalities, injuries, and "days away from work"
- Number of fires and explosions
- Costs of repairs and idle time after accidents

Other lagging indicators, though there is no general consensus regarding their characterizations as "lagging," are:

- On-site or public need to declare "shelter in place"
- Triggering of alarms, flares, or pressure relief devices
- Instances of material release (loss of primary containment)

Although there was an increased sophistication in industrial production during the 20th century, lagging indicators were still used to determine how "dangerous" a particular industry could be; however, the limitations of using lagging data to design prevention programs were recognized. Lagging indicators provide data about process safety failures retrospectively, and thus changes are only made after an issue occurs.

5. Leading Indicators –Active Monitoring

It was recognized in the petrochemical industry that for prevention programs, a more active approach to measure indexes of performance should be developed that systematically and actively monitors industrial operations (work systems, production, and safety-related equipment, etc.) to provide performance feedback before an accident occurs. Leading indicators are believed to be precursors, or predictors, of future safety performance so that undesirable safety outcomes can be prevented. Some examples of leading indicators are (Baker, 2007, API 754, 2011):

- Incidents of loss of content
- Worker participation in safety decisions
- Safe operation limit excursion

- Activation of safety instrument
- Overtime work—rest days taken--vacations taken
- Investment of resources and level of priorities for safety functions

Leading indicators proactively identify safety system deficiencies before the occurrence of negative and potentially serious outcomes.

6. OSHA and Lagging Indicators

One event that reshaped the safety field in the last century is the United States Occupational Safety and Health Act of 1971. For the first time, regulations at the federal level were implemented, which requires the collection of safety data uniformly and in a comparable format from sector to sector in industries. OSHA proposed to keep yearly records in the most basic lagging indicator of safety performance, which is the calculation of incident rates of work-related deaths, days away from work, restricted work, and medical treatment beyond first aid (OSHA 29 CFR 1904.0-46), as the systematic measure of personal safety.

The collection of these data is performed for general industry establishments with greater than 10 employees in the USA. National statistics have been collected since 1972 and represent the first attempt to use indicators to evaluate performance and to identify priorities for action.

After more than 20 years of experience obtaining these records (1970-92), OSHA confirmed that the number of cases and severity data of deaths, injuries, and illnesses obtained were a reflection of past personal safety performance and provided very little input for managing process safety risks. Because process safety accidents occur infrequently and are often unrelated in their casual factors, past incidents have a limited value in predicting future process-related incidents (Baker, 2007).

A vivid recognition that lagging indicators should not be used as performance indexes for the prevention of major chemical accidents in the chemical industry resulted from the Bhopal tragedy of 1984. The absence of systematic inspection regimes at the Union Carbide Plant in Bhopal and the lack of a preventive strategy illustrated the need to measure variables that are believed to be indicators of future safety performance. Data on workers' injuries and illnesses (even if collected properly) at the Bhopal plant would have had no predictive value in preventing the massive release of Methyl Isocyanate into the surrounding community. These findings were repeated in two investigations by the U.S. Chemical Safety and Hazard Investigation Board (CSB) in a number of major investigations of chemical fires and explosions in BP, Texas City, 2007, Tesoro, Anacortes, 2014, and the BP Macondo-Deepwater Horizon Oil Platform, which are discussed in this chapter (CSB, Investigations, www.csb.gov).

7. Indicators after Bhopal

Following the Bhopal tragedy, OSHA developed a Process Safety Management (PSM) standard (OSHA 29 CFR 1910.119) in a rule-making procedure that lasted from 1984 to 1992. The PSM standard's principal objective was to establish requirements for preventing or minimizing the consequences of catastrophic releases of toxic, reactive, flammable, or explosive chemicals. Since 1992, OSHA has required that chemical plants collect systematic documentation of the inspection and testing of work systems, production, and safety related equipment in addition to the traditional lagging indicators of personal injury, lost time, and sickness. The requirements include maintaining records for hazard analyses, safety operating procedures, the mechanical integrity of equipment, the management of change (MOC), audits, and pre-start safety reviews. This documentation offers a rich pool of leading indicators, which are measurable variables that could be indicators and precursors of future safety performance.

8. Personal Safety Metrics Indicators Are Not sufficient to Measure Major Accident Risks

Important distinctions in the use of indicators are the contrasting characteristics of indicators designed to measure elements of personal safety as opposed to elements that measure process safety. Personal safety indicators tend to be lagging indicators measured after failures have already taken place. These contrasting characteristics of personal and process safety indicators are summarized in Table 2.1, which shows that the scope of the measured indicators for personal and process safety, their capabilities as prevention tools, and the actors involved are different and have different applications. The table also illustrates that most personal safety measurements are lagging rather than leading indicators.

Table 2.1 Indicators: Process safety – personal safety in chemical production
Two distinct safety disciplines

	Process Safety	**Personal Safety**
Scope	Complex technical and organizational system	Individual injuries and fatalities
Prevention	Management systems: design, mechanical integrity, hazard evaluation	Procedures, training, Personnel Protective Equioment
Risk	Incidents with catastrophic potential	Slips, trip, falls, dropped objects, etc.
Primary actors	Senior executives, engineers, managers, operations personnel	Front line workers, supervisors
Safety indicators: Leading and Lagging Examples	HC releases, inspection frequency, PSM action item closure, well kick response, # of kicks (Pressured Gas Scapes)	Recordable injury rate, days away from work, timely refresher training, # of behavioral observations

Source: Author's own elaboration

In this chapter, a case study is described that illustrates the ways indicators (personal, process, lagging, and leading) interacted in an environmental catastrophe in the petrochemical chemical industry (Macondo-Deepwater-Horizon, Offshore Platform Explosion, Gulf of Mexico, April 2010). The evaluation of the indicators was completed through an investigation focusing on process safety management that was conducted by the U.S. CSB to identify the root causes of the incident and to formulate recommendations for prevention (CSB, 2011-16).

9. Chemical Safety Board (CSB) and Process Safety Management Investigations

The CSB is an independent investigative agency of the U.S. Federal Government with the responsibility to investigate root causes of major chemical incidents to apply the lessons learned to prevent their recurrence through recommendations to: U.S. Federal Regulatory Agencies (Occupational Safety and Health Administration and Environmental Protection Agency [OSHA, EPA]); Non-Governmental Industry Standards Organizations (NFPA, API, ASME, etc.); Companies & Industrial Sectors and Legislative Bodies (States, Local). The agency also has an extensive program for the dissemination of results (Press, Reports. Videos) (CSB, 2016).

CSB investigations typically examine process safety risks linked to incident events. Incident investigations usually identify precursor events that led to an incident. Similarly, performance indicators reveal safety gaps before an incident occurs. This approach is in line with the system approach described in the general system theory of management science. One of the key findings of the CSB investigations on Process Safety Management (PSM) was that the appropriate use of performance indicators is a predictor of safety performance and that the systematic application of process safety indicators drives continuous safety improvements in the chemical industry sector (CSB, ww.csb.gov. Investigations: BP Texas City, Tesoro, Anacortes and BP Macondo -Deepwater, 2007, 2014, 2015).

OSHA's requirements for record keeping have evolved from gathering frequency and severity of injuries and illnesses data (personal safety data) collected since 1972 to gathering more useful data that can predict safety performance. From 1992 - 1997, the chemical industry has been required to collect and update (every five years) additional workplace records of process safety management through the OSHA Process Safety Management federal standards.

OSHA required that by 1997, the chemical industry should have completed hazard analyses of facilities covered by the standard. Compliance with this requirement as well as with other PSM requirements has been mixed at best. The CSB found that failures to comply with the PSM standards were a common root cause of major chemical explosions and fires.

This was tragically confirmed after the CSB investigation of the refinery explosion and fire of the British Petroleum (BP) Texas City Refinery in March 2005, which killed 15 workers and caused $1.5 billion in damages and financial losses (CSB, 2007). This disaster occurred after more than ten years of the application of the OSHA PSM standards in the chemical industry. Subsequent, catastrophic chemical fires and explosions since 2007 that have been investigated by the CSB have shown little progress in the prevention of major incidents in the chemical sector. One of main lessons learned from the BP, Texas City disaster was the need for a separate focus on process safety as opposed to personal safety because personal safety (the basic lagging indicators) was not relevant to the explosion or fire, while measurable variables collected from process safety management data could have been predictors of future performance.

10. Chemical Safety Board (CSB) investigation of the fire and explosion at the BP Macondo-Deepwater Offshore Platform in the Gulf of Mexico in April 2010

Figure 2.1 BP Macondo-Deepwater Horizon Offshore Drilling Platform
in the Gulf of Mexico on 04/20/2016
Source: CSB (2014)

On April 20th, 2010, a multiple-fatality incident occurred at the site of the Macondo oil well approximately 50 miles off the coast of Louisiana in the Gulf of Mexico. The incident occurred during well-abandonment activities when the ultimate failure of a safety drilling device resulted in a well blowout. Hydrocarbon gas and liquid was released from the well and onto the rig, found an ignition source, and ignited and exploded on the Macondo-Deepwater Horizon (DWH) drilling rig's surface. The resulting explosions and fires led to the subsequent sinking of the rig, the deaths of 11 individuals, the serious injuries of 17 workers, and a spill of over five million barrels of crude oil, causing massive environmental damage. This incident marks one of the worst environmental disasters in U.S. history.

11. Incident Description

The incident occurred at Macondo well #252, which was located on the outer continental shelf of the Gulf of Mexico off the coast of Louisiana. The Macondo- Deepwater Horizon drilling rig was owned by Transocean (an international drilling operator) and leased to British Petroleum, which was the title holder and chief operator of the enterprise. The incident began as a hydrocarbon blowout followed by an explosion. After the exploratory drilling of the Macondo well had been completed, operations were in the process of being suspended. The activities of the drilling crew shifted to the process of Temporary Abandonment to permit the anchoring of a new production platform to initiate the routine pumping of crude oil. Temporary Abandonment consists of securing the well and removing all equipment above the wellhead. Once this had been accomplished, the Macondo-Deepwater Horizon drilling rig would have been replaced with a new production platform capable of producing hydrocarbons from the well. This description is paraphrased from the CSB investigation reports on the Macondo-Deepwater Explosion and Fire Investigation (CSB-Macondo, Volumes I and II, 2013-2014).

An early step in the abandonment process called for the installation of a cement barrier at the bottom of the well to seal off the hydrocarbon producing zone; however, in this case, the pressure testing of the cement job was misinterpreted, and the crew failed to realize that the producing zone was not sealed.

A subsequent step in the abandonment procedure called for the heavy drilling of mud in the well to be displaced with lighter seawater. Once this was completed, the pressure at the bottom of the well dropped enough to allow hydrocarbons to flow into the well and toward the surface of the Macondo-Deepwater Horizon platform. Subtle indications that the well was flowing toward the platform were evident from the data sent to personnel onshore; however, the crew failed to detect the hydrocarbons flowing in the well upwards for a significant period of time.

The force of the hydrocarbons accelerating upward in the well resulted in drilled mud gushing onto the drilling rig floor. A blowout was occurring. The crew took immediate action to close the blowout preventer (BOP, a safety structure designed to cut flow) and the seal in the well around the drill pipe; however, by this time, hydrocarbons were already passed the BOP and filling the mile-high riser connected to the rig. In addition to closing the blowout preventer around the drill pipe, the crew also closed the diverter at the top of the riser, an action meant to deflect the blowout to a safer location than the rig floor, but the flow from the diverter was left-routed to the default location, the mud-gas separator, which was not designed to handle a flow of the Macondo blowout's magnitude.

Mud and hydrocarbons rained down onto the rig floor as the mud-gas separator first vented high above the deck, shattered by the pressure of the blowout and then mechanically came apart. There were alternate pipes that could have been used to divert the blowout to over the side of the Macondo-Deepwater Horizon, but the hydraulically-operated valves for this line-up required manual activation, which did not occur. The hydrocarbons eventually found an ignition source, and explosions and fire ensued.

At some point after the explosions, the flow of hydrocarbons through the blowout preventer (BOP, a flow break off safety device) was re-established. Subsequent attempts to activate backup systems also failed to stop the blowout. The flow from the well continued from April 10th to July 15th, 2010, by which time the oil from the well constituted the largest offshore spill in U.S. history at more than five million barrels of crude oil. More importantly, 11 rig workers on the Deepwater Horizon lost their lives that day, and 17 were seriously hurt.

The desire to both understand the root causes of the incident and to prevent similar incidents has driven the CSB's continuing investigation, which has produced two reports (2014), with a final report scheduled to be released in the spring of 2016.

12. The CSB Findings on the Macondo-Deepwater Horizon Investigations

The CSB has identified several deficiencies in the safety management systems that were utilized by BP and Transocean at the time of the Macondo-Deepwater Horizon incident. The Swiss Cheese Method of consecutive deficiencies was used to illustrate the incident causes shown in Figure 2.3 (Reason, 2000). Four examples of deficiencies are highlighted. These include deficiencies in hazard assessments, procedures, MOC, and incident investigations.

Illustrated by the Swiss Cheese Model, these four deficiencies represent failed layers of protection that could have prevented the incident.

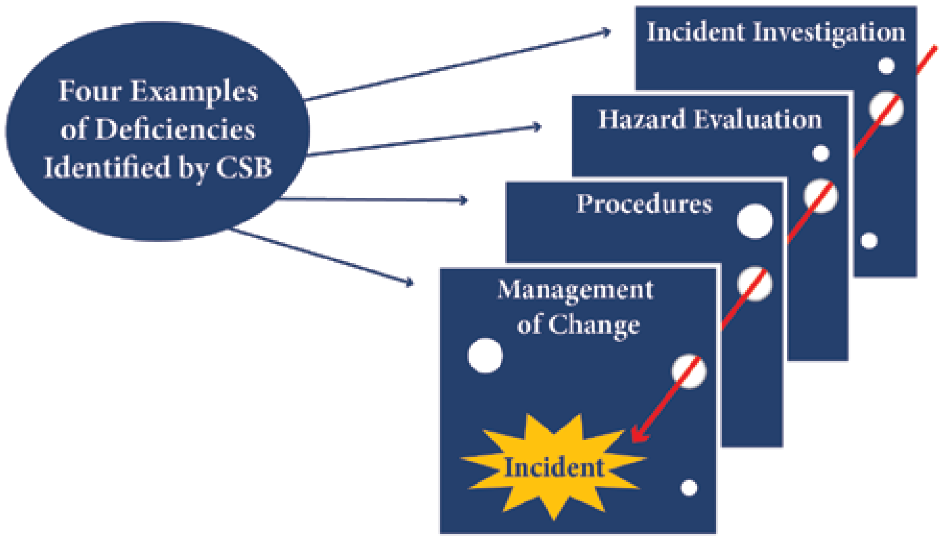


Figure 2.2 DWH Safety System Deficiencies
Source: CBS Indicators Public Meeting (2013)

The CSB found several instances of inadequate safety management systems on the Macondo-Deepwater Horizon platform. The investigators concluded that the development of appropriate indicators, in this case process safety indicators rather than personal safety indicators, would have predicted the failures and prevented the hydrocarbons from flowing to the surface of the rig. The CSB observed that indicators can provide insight and can alert personnel to subtle abnormalities before serious consequences occur. Thus, had indicators been identified and monitored for the safety management systems on the Macondo-Deepwater Horizon, perhaps the incident could have been avoided.

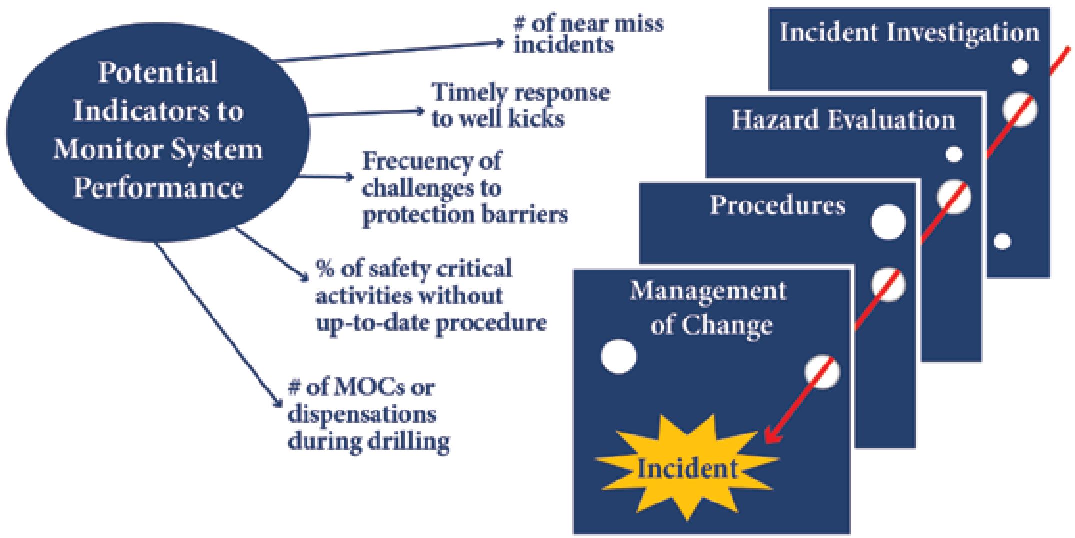


Figure 2.3 Safety Indicators Monitor System Performance
Source: CBS Indicators Public Meeting (2013)

The CSB suggested examples of pertinent safety indicators. These examples, which are provided in detail in Figure 2.3, illustrate the ways indicators can be developed to aid performance.

1. Incident investigations, especially into near misses, provide tremendous leading indications of risk. A high frequency of near-miss barrier challenges suggests misunderstood risk. It also provides a warning against the normalization of deviance, which is an acceptance that the activation of a safety barrier is normal. Two previous well-kicks (vigorous hydrocarbon escapes from the well) that occurred within the last few months were ignored. Using "number of kicks" as a leading indicator (such as the time to respond to an actual incident) could provide important data to improve well control responses.

2. A proper hazard assessment should identify the initiating events that can cause high-consequence incidents. The associated risk should be evaluated, and the protection barriers that prevent a severe consequence should be verified. A good leading indicator could be the frequency of challenges to protection barriers. If they are being challenged frequently, perhaps additional secure barriers may be needed.

3. Hazard analyses and MOCs identify activities that are critical to safe operations. A good leading indicator could be the percentage of these activities that have up-to-date procedures. Initially, this indicator could evaluate whether effective procedures exist. As the safety management system matures, the indicator could evolve to evaluate whether procedure verifications and updates occur at proper frequencies.

4. Comparisons of the number of MOC analyses (special hazard analyses when changes are implemented) completed during pre-engineered and planned activities, such as drilling, across different rigs could indicate the health of the MOC system. A higher than average number of MOCs might suggest that the well is much different than anticipated and requires extra oversight. Conversely, a lower than average number of MOCs could indicate that changes are being made that bypass the MOC system. Regardless, an audit of the current versus original drill plans would indicate the changes that should have been evaluated, which could also serve as a leading indicator of the health of the MOC system.

Based on the results of the investigation, the CSB emphasizes that indicators for these four findings can be developed to improve safety system performance and prevent potential catastrophic incidents such as Macondo. These are the performance process safety management indicators that must be recorded routinely to develop a baseline and to determine trends. Instead, the CSB's findings show that BP and Transocean's approach to safety demonstrated a clear over-emphasis on indicators of personal safety at the expense of major accident prevention indicators.

Paraphrasing safety expert Andrew Hopkins, the reality is that companies and their employees tend to focus on indicators of safety that are customarily measured at the expense of new indicators that are not measured. In this case, an overemphasis on apparently successful personal safety indicators leads to complacency when evaluating process safety indicators.

13. World Use of Process Safety Indicators

Offshore petrochemical drilling operations and trade associations operating in other regulatory regimes outside the U.S. have developed effective indicator programs, and they recognize the value of leading process safety indicators and use those indicators to drive continuous improvement. These countries (Norway [PSA], the United Kingdom [HSE], and Australia) have a mature offshore oil production industry and have integrated the use of performance indicators into their preventive safety operations.

In the UK, the regulator works in a tri-partite group that has established three key performance metrics and targets for improvement, such as reducing hydrocarbon releases by a certain percentage each year. Norway's PSA also partners with industry groups and unions in a program that collects several leading and lagging indicators, and they assess the health of well safety barriers and other leading and lagging performance metrics.

14. Findings and Recommendations of CSB for the BP Macondo Deepwater Horizon Catastrophe

BP, the platform owner, and Transocean, the drilling operator, had multiple safety management system deficiencies that eventually became root causes of the Macondo incident. Safety approaches used by the companies, U.S. regulators, and U.S. trade associations did not adequately focus on major accident hazards. Rather, the systems used for measuring safety effectiveness focused on personal safety and infrequent, lagging indicators.

The CSB has made specific recommendations to the U.S. offshore regulators with the aim to achieve a greater impact on major accident prevention through the development of a leading and lagging process safety indicator program.

It was also observed that companies and trade associations that operate in other regulatory regimes outside the U.S. have developed effective indicator programs, and they recognize the value of leading indicators and use those indicators to drive continuous improvement.

15. Key CSB Finding: Personal Safety Indicators Are Not Sufficient to Measure Major Accident Risks

As part of its public reporting to the Securities and Exchange Commission, Transocean (TO) discussed how it measures safety performance and presented actual performance through annualized statistics. Transocean measured overall safety performance using two metrics: Total recordable injury rate (TRIR) and Total potential severity rate (TPSR). According to the TO Asset Management Handbook's definition, its potential severity per incident metric "relates only to potential personal injury." (CSBMacondo, Volumes I and II, 2013-2014). Both lagging indicators are descriptive of personal safety experience rather than indicators of process safety performance.

Nevertheless, in the aftermath of the Macondo catastrophe, TO gave itself a zero score for the TRIR because astonishingly, the 11 fatalities were not classified as "injury rates." The TPSR score was high enough that its top-level corporate executives received financial bonuses. Safety performance was rewarded with monetary bonuses despite the company experiencing its largest multi-fatality incident with devastating economic, environmental, and human consequences.

Transocean's Health and Safety Manual states that the "key tools" within its Health and Safety Management System are indicators specifically focused on managing personal risk—not major accident risk. There were also additional behavior-based safety indicators collected by the company (known as the START Program) focused on the efforts of the rig crew to plan a work task and the behaviors used to carry them out.

Like the TRIR and TPSR, these tools are specifically focused on managing personal risk—not major accident risk. Daily START card completions have been identified by Transocean as a key performance indictor and have been included as a corporate measure for rig performance. In summary, it was found that the company overemphasized the use of these behavioral programs as their primary means of measuring the safety performance of its processes.

16. Conclusions

The prevention of major accidents must be part of the design of a production system. Using the system approach theory, it is possible to improve industrial processes by using safety performance indicators (quantitative and qualitative). The definition and analysis of the indicators presented in the CSB BP Macondo Deepwater Explosion investigation could then be incorporated into the management of enterprises by using them as predictive tools to validate prevention strategies.

Despite some significant progress with process safety indicator implementation in the downstream oil industry, in the offshore sector, these critical warnings do not seem to have been heeded to prevent catastrophic incidents. Thus, industry management, regulators, and the workforce must work together to develop more effective process safety indicator programs for onshore and offshore energy operations.

Catastrophic mishaps deny the very possibility of industrial production with the total breakdown of the business enterprise, let alone its sustainability. Management science suggests a system of "social accounting" of human enterprises by developing a set of comprehensive indicators to establish what is known about progress toward general, acceptable goals in the petrochemical and the industrial sector in general. Applying the system approach theory in the development of these indicators will define benchmarks and trends of industrial operations that will in turn provide policy makers with a method to create and evaluate new catastrophe prevention tools.

References

Van Gigch, J.P. 1971. Applied General System Theory. First Edition. Harper & Row, Publishers. NewYork

Van Gigch, J.P. 2006. Teoria General de Sistemas. 3ra Edicion. Editorial Trillas, Mexico

API/ANSI Standard 754. 2010. Recommended Practice (RP): Process Safety Performance Indicators for the Refining and Petrochemical Industries. American Petroleum Institute (API), Washington DC

BP U.S. Refineries Independent Safety Review Panel. 2007. Report of the Panel to BP and CSB. CSB. Washington DC

CSB, U.S. Chemical Hazard and Hazard Investigation Board. 2014. Tesoro Refinery Fatal Explosion and Fire, Anacortes WA. www.CSB.gov. Washington DC

CSB, U.S. Chemical Hazard and Hazard Investigation Board. 2007. BP Texas City: Refinery Explosion and Fire.Texas City, TX. www.CSB.gov. Washington DC

CSB, U.S. Chemical Hazard and Hazard Investigation Board. 2014. Explosion and Fire at the Macondo Well. Volumes I and II, Mississippi Canyon Block # 252, Gulf of Mexico. www.CSB.gov. Washington DC

CSB, U.S. Chemical Hazard and Hazard Investigation Board. 2012. Public Meeting: Offshore Safety Performance Indicators,Preliminary Findings on Macon do Incident. Houston, TX www.CSB.gov. Washington DC

National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling. 2011. Report to the President. U.S. Government Printing Office, Washington DC

Perrow, C. 1999. Normal Accidents: Living with High Risk Technology. Basic Books, Princeton University Press. New York

Reason, J. 1990. The contribution of latent human failures to the breakdown of complex systems. Philosophical Transactions of the Royal Society (London), series B. 327: 475-484.

Reason, J. T. 1997. Managing the risks of organizational accidents. Aldershot, UK: Ashgate Publishing Limited.

3. SPRAY POLYURETHANE FOAM AND SUSTAINABLE CONSTRUCTION: CHALLENGES AND OPPORTUNITIES

Anila Bello, Alicia McCarthy, Dhimiter Bello

1. Introduction

Sustainable construction is the planning, design, and construction of buildings to improve the environmental quality (thermal, visual, and acoustic) while being resource-efficient (materials, energy, and water) and minimizing the impact on the natural environment throughout the lifecycle of the building *(UNEP, 2016)*. The definition of sustainable construction has evolved over time. Originally, the goal was to manage limited resources, such as energy, and to protect the environment, but over time, the emphasis has evolved to include materials and construction technology *(Buyle et al., 2013)*. For the U.S. Green Building Council (USGBC), sustainable construction applies to buildings and their sites, interiors, operations, and the communities and people around them. The practice involves creating and using healthier and more resource-efficient models of construction, renovation, operation, maintenance, and demolition while considering the environmental health aspects of green building *(Buyle et al., 2013, USGBC, 2016)*.

The terms "sustainable construction" and "green building" are commonly used interchangeably. To evaluate the environmental performance of green buildings, the USGBC has established the Leadership in Energy and Environmental Design (LEED) rating system, which is the most widely used green building rating system globally. The LEED criteria focus on sustainability, indoor air quality, materials, resources, energy, and atmosphere. As of August 2015, there were more than 72,500 LEED building projects located in over 150 countries. According to the USGBC, LEED certification of U.S. buildings between 2015-2018 is estimated to deliver $1.2 billion in energy savings, $149.5 million in water savings, $715.2 million in maintenance savings, and $54.2 million in waste savings *(USGBC, 2016)*.

Climate change has recently been linked to sustainable construction. Countries around the world recognize that climate change is a growing threat to the development and welfare of their citizens. In the Paris climate conference in December of 2015, 195 countries adopted the first legally binding global climate agreement, which established a plan to slow the rate of climate change and rising global temperatures. Part of this agreement relies on investments in energy efficient and environmentally friendly construction options that are consistent with sustainable development principles. Improvement in energy efficiency can reduce greenhouse gases emissions and their carbon footprint in the environment.

Building insulation is one of the most effective energy efficient technologies that can significantly reduce the level of the emission of greenhouse gases. Spray polyurethane foam (SPF) is commonly promoted as a "green" building material because its use contributes significantly to home and building energy savings. The use of SPF has experienced the fastest growing trends in recent decades compared to other building insulation products, including fiberglass, rock and slag wool, and blown cellulose. In 2015, SPF sales reached about $1 billion, and manufacturers reported 460-490 million pounds of SPF sold in the U.S. and Canada *(Kavanaugh, 2016).*

The sustainability of SPF has mainly been associated with the energy efficiency of buildings. Energy savings resulting from home insulation qualify for tax credits under the American Recovery and Reinvestment Act of 2009. The tax break allowed for a credit of 30% for the purchase of energy efficient products in 2010 *(IRS, 2016).* According to the SPF industry, the sustainability of SPF contributes to energy efficiency, and notable progress has been made *(Doug Kramer September 2016).* Improvements in blowing agent technology is a good example of this progress. Motivated by the Montreal Protocol in 1989, which required the elimination of halogenated hydrocarbons known to deplete the ozone layer, the use of chlorofluorocarbons (CFCs) was phased out, and the technology transitioned to the use of hydro chlorofluorocarbons (HCFCs). In 2014, the SPF industry made the official substitution to the fourth generation of blowing agents, hydrofluoroolefins (HFOs), which are non-ozone depleters with a lower global warming potential *(Doug Kramer September 2016).* Other advantages of SPF include its ability to adhere to various surfaces, including concrete, wood, and steel, which allows for moisture seal and mold prevention. Furthermore, the prevention of ice dams has motivated homeowners to insulate their houses with SPF. The demand for SPF insulation is higher during the winter months, and this has increased the number of small contractors entering the insulation market each year.

Despite the energy savings, the sustainability claims, and other benefits related to SPF insulation, its use is not openly encouraged at the federal level. The Environmental Protection Administration (EPA) promotes insulation for energy efficiency purposes, but it remains concerned about the potential toxic health effects of exposure to various ingredients in SPF generated during and possibly post-SPF applications *(USEPA, 2016).* To summarize the public health concerns related to the use of SPF, this chapter provides background information on the types of SPF, the chemical compositions, and the adverse health effects of the chemicals in SPF mixtures.

2. Spray Polyurethane Foam Products – Chemistry and Technology

The chemistry of polyurethanes was invented in 1937 in Germany. The first product created in 1953 was applied as a liquid, and it expanded into foam *(Bayer Material Science).* In the U.S., the demand for SPF increased sharply during the 1970s due to an energy crisis. Energy savings from SPF applications in roofing were first documented in the 1980s.

Polyurethane foam is produced as a result of an exothermic reaction between isocyanates and polyols in the presence of catalysts. SPF products typically consist of two-part systems, Part A and Part B, which are combined at a 1:1 ratio at the time of application. The Part A component includes an aromatic isocyanate (discussed later), whereas the Part B component usually consists of a mixture of chemicals that contain polyols, catalysts, blowing agents, flame retardants, and surfactants *(Sonnenschein, 2014).*

Figure 3.1 Spray foam insulation of (A) a new building (open-cell type) and B) the basement of an old house (also open-cell). The second worker in (A) is trimming the foam with a blade saw.
Source: Author's own elaboration

During the application process, Parts A and B are pumped from the supply tanks and distributed through hoses to the spray gun. The initial reaction of the A and B sides begins at the spray nozzle when both parts are mixed in real time. The exothermic polymerization (curing) process begins immediately. Distributed in a stream flow, the foam vigorously expands as it reaches the intended surface. The curing rate, which is the time required for the foam to fully polymerize, largely depends on the SPF formulation chemistry and environmental conditions, such as temperature and humidity. The polymerization of the SPF begins within seconds of the initial mixture and may be completed between a few hours and 48 hours depending on the product type. Once the SPF has been applied, expanded, and cured, the foam surface can be trimmed or cut to remove excess foam from certain surfaces and/or to create a flat surface against the studs. Excess SPF is disposed of as regular non-hazardous waste. Figure 3.1 depicts a typical SPF application. Trimming is shown in Figure 3.2.

There are several types of SPF used for insulation and roofing systems. These classifications are related to the density of the material and cell structure. Open-cell SPF is commonly used in residential buildings and has a nominal density of 0.4-0.7 pounds per cubic foot (pcf) *(SPFA, 2012)*. The insulation power is determined by the R value, which is estimated based on the thermal conductivity per inch of material. Higher R values indicate better insulation. The R value for **open-cell** foam ranges from 3.6-4 per inch thickness. Water is often used as a chemical blowing agent for this type of SPF insulation. The water reacts with the isocyanate to form carbon dioxide gas that expands the mixture into foam. Due to its open cell structure, this type of SPF insulation is filled with air and therefore has a similar thermal conductivity to fibrous insulations *(SPFA, 2012)*. **Closed-cell** SPF has a nominal density of 1.7-2.3 pcf and a structure in which more than 90% of the cells are closed, making it more resistant to moisture. The composition of closed-cell foam includes physical blowing agents, such as fluorocarbons, which are volatilized from the heat of reaction and are retained within the closed cells, resulting in lower thermal conductivity and better insulating performance with R values ranging from 5.8 to 6.8. The high density and the ridged structure of closed-cell SPF can also provide additional structural integrity for a building. The **SPF Roofing System** is similar to the closed-cell SPF in structure, but it has a much higher density to provide the higher compressive strength required to support a low-sloped roof. The density of roofing SPF ranges from 2.5 to 3.5 pcf. Once the roofing SPF is cured, it is covered with a protective surface. Typically, a spray applied elastomeric coating is used to provide increased durability, weatherproofing, and aesthetic appearance *(SPFA, 2012).*

Figure 3.2 Trimming and removal of closed-cell foam using a powered brush tool. Source: Author's own elaboration

Commercially available SPF systems include: i) two component high-pressure systems, ii) two component low-pressure systems, and iii) single component systems. Professionally trained contractors primarily use the high-pressure systems in commercial applications, which feature a more proportioned system. This system is comprised of two 55-gallon drums containing the two-part, A-side and B-side, chemical components as well as a high-pressure air compressor, a computer aided reactor (mixer), hoses, and spray guns. Supplied air respirators (SAR) and ventilation fans are also common auxiliary components. The total system is usually transported in an enclosed trailer unit. Two component, low-pressure systems are available "off the shelf" to private consumers. These systepolyoms are similar to the high-pressure systems but are typically distributed in smaller volumes, three to five-gallon size (each side), used for smaller insulation jobs. A complete system includes two cylinders under pressure, a gun hose assembly, and spray nozzles. Single component foam systems can be purchased "off the shelf" in 12 or 24 oz. cans. They contain the isocyanate (MDI), which undergoes further reaction when exposed to ambient moisture. Single component systems are typically used for smaller patching jobs or gap filling.

3. Chemical Composition of Spray Polyurethane Foam

Part A components:

Isocyanates. Isocyanates are highly reactive chemicals of low molecular weights containing the functional group N=C=O. Isocyanates are either aromatic (one or more aromatic rings) or saturated (aliphatic and alicyclic). Isocyanates are classified based on the number of N=C=O groups in the molecule into monoisocyanates (one NCO), diisocyanate monomers (two NCO), or polyisocyanates (multiple NCOs). Two NCO groups in diisocyanate monomers allow them to undergo direct polymerization reactions with alcohols to form polyurethanes. Polyisocyanates formed by the condensation of up to 10 monomeric isocyanates are called oligomers. Polyisocyanates contain multiple free NCO groups and can further react with other active hydrogen compounds, such as polyfunctional alcohols (polyols) or amines, to form polymeric products of even greater complexities *(Sonnenschein, 2014, Meier-Westhues 2007)*. The most common isocyanate species used in part A SPF formulations are 4,4' diphenylmethane diisocyanate (MDI) and polymeric MDI (pMDI). pMDI contains about 50% MDI (two aromatic rings), and the rest is comprised of higher molecular weight oligomers (three, four, and five rings).

Part B components:

The B-side is a mixture composed of polyols, catalysts, blowing agent fire retardants, surfactants, and other minor additives *(Bayer Material Science, Meier-Westhues 2007, Sonnenschein, 2014)*. Table 3.1 summarizes the main components and their percentages in Part B mixtures of three types of foams.

Table 3.1 Part B formulations of spray polyurethane foam (Bayer Material Science)

Chemical	Low density foam	Medium density foam	Roofing
Polyol-Polyester	-	45.0%	35.0%
Polyol Polyether	35.0 %	-	-
Fire Retardant -TCPP	25.0%	4.0 %	8.0%
Fire Retardant - Brominated	-	6.0%	-
Blowing Agent –Reactive (H20)	23.5%	2.0%	1.6%
Blowing Agent (HFC)	-	8.5 %	7.5%
Catalyst-Amine	6.0%	3.0%	2.0%
Catalyst –Metal	-	0.5%	0.4%
Surfactants	0.5%	1.0%	1.0%

Polyols are the main active ingredient of Part B. They crosslink with isocyanates to form a polymeric network and comprise about 35-45% of part B mixtures. Two types of polyols are commercially available, polyethers and polyesters. Polyethers are more commonly used due to a lower cost and greater stability. Glycols, such as ethylene glycol and 1,4 butanediol, have lower molecular weights compared to the polyols and are used for chain extensions.

Amine catalysts may be primary (NH2), secondary (-NH-), or tertiary (-N-) depending on their chemical structure. They are typically found in 2-6% of the total formula. Catalysts are used to control the speed of the polymerization reaction and the curing rate of SPF. The catalytic activity of amines is based on their free pair of electrons from the nitrogen atom. Amine catalysts with low boiling points, such as triethylamine, are volatilized during the exothermic reaction.

Blowing agents can be low boiling solvents that act as the principle source to blow the foam. When the main isocyanate-polyol reaction occurs, the temperature reaches 1300C, which is high enough to vaporize the solvent and to provide supplementary gases that expand the foam. The typical percentage by volume of blowing agents found in the B side ranges from 1-23%. Water also serves as a blowing agent for open cell foams. Water-isocyanate reactions release CO_2, which in combination with blowing agents produces softer foam. Examples of physical blowing agents include hydroflourocarbons (HFCs), such as trans-1,2-dichloroethylene. Until the early 1990s, the primary blowing agent was chloroflorocarbon CFCl3, but it was phased out in 1995 due to environmental concerns regarding ozone layer depletion.

Fire retardants are used in foam insulation to meet fire code requirements. Foam insulation with flame retardants may catch fire and burn vigorously, produce a thick black smoke, and spread the fire to other combustibles. Flame-retardants are used at 4-25% of the B side formulation. The most common flame retardant is tris 1-chloro 2-propyl phosphate (TCCP), which is a chlorinated organophosphate.

Surfactants are added to modify the size and integrity of foam cells during foam expansion. Their function is to reduce the surface tensions, emulsify the mixture, stabilize cell walls during foam creation, and reduce the effects of any solids in the mixture. Surfactants comprise ~ 2% of the B side. The most commonly used are non-ionic surfactants.

4. Health Effects Associated with Exposure to Spray Foam Insulation Chemicals

Isocyanates: Exposure to isocyanates in the SPF industry is largely dependent on the species found in the formulation. Isocyanates can be generated during the application process in the forms of vapors, aerosols, and dust. Workers are potentially exposed to unreacted monomers, prepolymers, and polyisocyanates during mixing, formulation, and application tasks. Acute exposure to MDI can cause sensitization and asthma in humans. Dermal contact can cause skin irritation and contact dermatitis. Isocyanate exposures are the leading cause of occupational asthma. Both inhalation and dermal exposures to isocyanates are believed to contribute to the development of occupational asthma *(Bello et al., 2007)*. Chronic inhalation exposure has been linked with other respiratory conditions among exposed workers. Individuals already sensitized at exposure levels above the occupational standards may develop symptoms even at very low exposure levels to MDI *(Redlich et al., 2006)*. Occupational exposure is a concern because sensitization or asthma has developed even in cases when occupational exposure is below standards *(Wisnewski et al., 2013)*. Data from animals suggest that occupational exposure to MDI can increase the risk of cancer; however, epidemiological studies have yet to establish any evidence. Although EPA has classified MDI as a Group D, not classifiable as a human carcinogen, the aromatic isocyanates may be potential carcinogens based on comparisons of TDI carcinogenic effects *(U.S. EPA, 2011)*.

Amines catalysts: Exposure to airborne amine catalysts may result in irritation to the eyes, skin, and respiratory system *(Michelotti et al., 2015)*. Acute Inhalation has been known to cause glaucopsia, or "halo vision," in the eyes, and this effect is characterized by fogging of the vision due to the swelling of the outer layer of the cornea. Skin contact may cause irritation and burns, including redness and swelling. Additional symptoms may include chest pain, circulatory collapse nausea, and gastrointestinal bleeding. Bis(2-dimethylaminoethyl) ether, a tertiary amine commonly used in formulations, has been known to contribute to overall exposure through the cutaneous route, including mucous membranes and the eyes, due to contact with vapors, liquids, and solids *(U.S. Consumer Product Safety Commission, 2012)*.

Flame Retardants used in spray polyurethane foam are mostly halogenated compounds. Brominated and chlorinated flame retardants are recognized as global contaminants that attribute to adverse health effects in both animals and humans. Health effects include cancer, reproductive or developmental disorders, and impacts on neurologic functions. Other adverse health effects associated with flame retardants include endocrine and thyroid disruption *(WHO, 1998)*. Tris 1-chloro 2-propyl phosphate (TCCP) is the most commonly used flame retardant in spray foam insulation. Data from the U.S. EPA Chemical Data recording database show that in 2012, nearly two million pounds of TCPP were used for construction products. According to the US EPA, TCPP exposure in experimental animals was shown to cause adverse health effects on reproduction, developmental, and neurological systems. It is important to note that TCEP and TDCPP, which share structural similarities to TCCP, are listed as substances known to cause cancer in human under California Proposition 65 *(US EPA 2011)*.

Blowing Agents: The first generation of blowing agents was composed of chlorofluorocarbons (CFCs), which have extremely high ozone depletion potential. The second generation was hydro-chlorofluorocarbons (HCFCs); however, because HCFCs were found to have high global warming potential, they were substituted by the next generation of blowing agents, hydrofluorocarbons (HFCs), which are commonly found in modern-day SPF products. HFCs' potential for greenhouse gases and contributions to global warming *(SPFA, 2012)* are higher compared to carbon dioxide's impact, and they can persist in the environment for a long period of time (up to hundreds of years). Excessive exposure to HFCs can also be damaging to the brain and heart, and their carcinogenicity is still under debate *(Howard et al., 1996)*. In 2014, the SPF industry made the official substitution to the fourth generation of blowing agents, hydrofluoroolefins (HFOs), which are non-ozone depleters with a lower global warming potential.

Glycols and glycol ethers are commonly used in the B-side formulations for SPF. The SDS supplied by the foam manufacturers often lists them as a trade secret under the generic name of "glycol derivative". Health effects for repeated exposure from ingestion and inhalation to ethylene glycol include eye lacrimation, general anesthesia, respiratory stimulation and effects to the central nervous system. It is considered a skin, eye, and mucous membrane irritant *(USEPA, 2000)*.

5. Public Health Concerns

The majority of health concerns surrounding SPF applications relate to isocyanates (A part), and they include occupational asthma, hypersensitivity pneumonitis, skin contact dermatitis (allergic and irritant), and irritation of the skin, eyes, mucus membranes, and the respiratory tract. Much less is known about exposure and the adverse health effects of Part B components. The known health impacts include potential sensitization by certain amine catalysts, eye and upper airway irritation (amines), respiratory irritation (ethylene glycols), and possible endocrine disruption (by flame retardants).

Concerns related to consumer exposure

Emissions or off-gassing of chemicals from SPF can increase the risk of exposure to homeowners and other building occupants even after SPF application *(Redlich et al., 2006).* Although published data are limited in the literature, 24 hr after the SPF application, airborne isocyanate concentrations are non-detectable if the foam has been applied according to the manufacturer's recommendations. It is generally believed that SPF application conditions that are out of the required specifications (such as the A/B off ratios) and lower application temperatures can play important roles in faulty SPF applications. An improper balance between the A- and B-sides may lead to much higher isocyanate exposure during application or to emissions of some of the additives post-application.

A recent study by *Huang and Tsuang (2014)* presented a number of health effects reported by 13 adults after SPF application in 10 residential houses. Among the symptoms, the homeowners reported acute burning eyes, sinus congestion, throat irritation, cough, and chest tightness. The symptoms disappeared after they left their homes but reoccurred when they returned. Three subjects reported gastrointestinal symptoms and skin rashes. The authors explained that these concerns were genuine and were not driven by any monetary compensation. According to the data, these homes were improperly retrofitted, and product mixing and ventilation were not performed according to the recommendations. In most of the cases, the homeowners did not leave their homes while the SPF was being applied. In two cases, the spouses were not in the homes during the spray application and did not show any symptoms, suggesting that the risk could be reduced if homeowners are not allowed to be in the home during SPF insulation.

Several case reports have indicated that homeowners complain about the unpleasant odors, such as "fishy" and "ammonia-like" smells, that can persist for several months after SPF application. Because isocyanates are reactive chemicals, these odors may not be due to the isocyanates but to the chemicals from the B-side, such as amine catalysts; however, the compounds responsible for the symptoms reported are unclear. Emissions of VOC after application could cause homeowners' symptoms; however, further research is needed to identify the specific VOC. Exposures to MDI could be responsible for the symptoms if the residents are present during application; however, MDI has not been found in indoor air after SPF application has cured. The "safe re-entry time" for residents, i.e., time post-SPF application that is deemed safe for building re-occupancy, is often 24 hr for two component SPF applications. Although it is recommended that residents should not be present inside the building during the SPF application, this cautionary information is not always provided to consumers.

The SPF industry has recently established guidelines for SPF applications that could help homeowners, and professional certification programs for contractors are offered (http://www.sprayfoam.org). The spray foam website provides information about health concerns and actions that can be taken to prevent exposure to SPF for both homeowners and professionals. Furthermore, there is a risk of exposure for "Do It Yourself (DIY)" consumers who use low pressure two-component foams or one component insulating sealants. The industry provides guidance regarding the application process and ways to protect users from exposure, and it is also recommended that homeowners consult these websites before using DYI products; however, it is likely that consumers are not aware of hazards from products containing uncured MDI because they do not always read product labels.

The U.S. EPA provides online support with important information for homeowners and the public to prevent exposure to SPF. Homeowners have access to checklists that help consumers avoid potential risks from SPF. In cases of health concerns, the EPA recommends that consumers file an incident report with the U.S. Consumer Product Safety Commission on SaferProducts.gov. In April 2011, the EPA announced an action plan focused on the potential health effects that may result from exposure to consumers using products containing uncured MDI or incidental exposure to the general population while such products are used in or around buildings, including homes or schools *(US EPA, 2011)*. Furthermore, MDI is regulated under the Clean Air Act as a hazardous pollutant. The Toxic Control Act (TSCA) section 8 (e) requires chemical manufacturers, importers, distributers, processors, and applicators to inform the EPA of the usage of isocyanates and other SPF compounds. In 2009, a partnership between the EPA, OSHA, NIOSH, and the Consumer Product Safety Commission was established to address exposure to isocyanate and other chemicals during SPF application. These agencies are working with the industry to ensure hazard alertness and that best practices are followed to prevent exposure *(U.S. EPA, 2011)*.

Occupational exposure concerns

Occupational exposure to SPF components occur during both its production and application, mostly through breathing aerosol particles during application and through skin contact. Exposure during application can impact workers who perform spraying as well as bystanders present in the building (e.g., electricians, plumbers) because the aerosol particles generated can travel throughout the area. Self-employed workers are at a high risk because they are not subject to OSHA occupational exposure limits and are not required to receive health or safety training. Workers with histories of respiratory allergies, asthma, or prior isocyanate sensitization are at a higher risk for adverse health effects. Several factors can determine worker exposure, including indoor or outdoor application, ventilation, time of year conditions, type of foam, e.g., open or closed-cell foam, and training and experience with the applicators. An improperly balanced mixture of the A- and B-sides may also lead to off-gassing of chemicals for months or even years, although the exact length of time is not known.

Exposure data to SPF components other than isocyanates in humans, including in occupational settings, are still lacking. Most existing SPF exposure data relate to isocyanates. Lesage et al. (2007) reported airborne exposure to MDI during spray foam insulation in five residential homes in the U.S. and Canada. Concentrations of MDI for personal samples ranged from 0.07-2.05 mg/m^3, and the majority exceeded the OSHA PEL celling of 0.2 mg/m^3 and decreased rapidly after application (*Lesage et al., 2007).* Lower exposure levels for SPF applicators have been reported by Bilan et al. (1989) and Crespo and Galan (1999), with the highest values of 1.32 and 0.4 mg/m^3, respectively. Several more recent studies have focused on assessing the levels of urinary biomarker of MDI (the corresponding diamine MDA) to evaluate the efficacy of controls in the workplace. A study in France found higher post-shift MDA levels among 169 workers exposed to MDI than pre-shift *(Robert et al., 2007),* indicative of isocyanate uptake. A study in Finland measured dermal and inhalation exposure to MDI during polyurethane applications, with and without respirators, as well as urinary MDA, and found low MDA urinary levels, but MDA excretion patterns post-shift suggested possible MDI dermal uptake *(Henriks-Eckerman et al., 2015).*

The Center for Disease Control (CDC) has reported several case studies on worker exposure to MDI in various workplaces. In one case, a maintenance worker was exposed and became ill after repairing an MDI foaming system in 1994. The worker suffered from reoccurring respiratory illness due to isocyanates. Although the worker quit his job after being diagnosed with symptoms related to exposure, he experienced coughing and loss of lung function. His condition worsened with weakness, sweats, muscle aches, and shortness of breath. After his death, the worksite was evaluated and was found to have detectable air concentrations of MDI due to a lack of proper ventilation systems in the foaming maintenance area. Employees who worked with the foam reported seeing vapors and aerosols rising into the faces of employees as well as skin contact with the curing foam.

Reducing airborne exposure from SPF insulation requires the careful use of personal protective equipment (PPE), such as Tyvek coveralls, head and shoe covering, gloves, and supplied air respirators (SAR). Disposable polypropylene suits should be used to avoid exposure rather than street clothes, and gloves should be made from nitrile or butyl rubber. Workers should wear full-face respirators or chemical safety goggles with a respirator when handling or applying SPF. Particle filters will not protect workers from MDI vapors. Combination N-95 filter/organic vapor cartridges (OVC) are often used in the workplace. SARs provide more protection compared to OVC respirators. Workers should wash their hands before and after breaks and when leaving work. For outdoor work, workers should stop spraying under windy conditions to avoid bystander exposure.

Federal and state regulations help protect workers from SPF chemical exposure. OSHA has established a permissible exposure limit (PELs) for exposure to MDI. When occupational exposure levels exceed the PELs, the use of PPE is required when engineering controls (e.g., ventilation) or administrative controls are not feasible *(OSHA, 2013)*. Table 3.2 presents the relevant occupational exposure limits for aromatic isocyanates set by different regulatory national and international agencies *(Bello et al., 2004)*. Table 3.3, which was prepared by the American Chemistry Council (2011), reports the occupational standards set for some polyurethane amine catalysts *(U.S. Consumer Product Safety Commission, 2012)*. OSHA requires that employers who work with hazardous substances, such as isocyanates, are trained to work with them safely, that they must make safety data sheets available, and that respiratory protection should be available and provided to employees.

Table 3.2 Current U.S. (OSHA, NIOSH, ACGIH), UK-HSE, and Swedish occupational exposure limits (OEL) (mg/m³ air) for aromatic isocyanates. Bracketed values represent the equivalent standard in mg NCO/m³

Isocyanate Species		**OSHA PEL**		**NIOSH REL**		**ACGIG TLV**		**US HSE OEL**		**Swedish OEL**	
		TWA 8hr	Ceiling 15 min	TWA 10hr	Ceiling 10 min	TWA 8hr	STEL 15 min	TWA 8-hr	Ceiling 10 min	TWA 8-hr	STEL 15 min
Aromatic Diisocyanates	TDI	-	140 (68)	CA-LFC[a]	-	36 (17)	140 (68)	-	-	-	-
	MDI	-	200 (67)	50 (17)	200 (67)	51 (17)	-	-	-	-	-
Universal Standard	Total NCO[b]	-		-	-	-	-	(20)	(70)	(20)	(44)

a) NIOSH considers TDI to be an occupational carcinogen (CA) and recommends that exposures be reduced to the lowest feasible concentration (LFC).

b) Total reactive isocyanate group in mg NCO group/m³. The standard applies to all isocyanate species (monomers, polyisocyanates, and their mixtures) regardless of their origin.

Table 3.3 Permissible exposure levels and threshold limit values of some polyurethane amine catalysts [(A)]

Chemical Name	CASRN	Exposure Limit, ppm (Source)			
		PEL	STEL	TLV	TWA
Dimethylcyclohexylamine, N,N-	98-94-2	NR	5 ppm (Ontario)	NR	NR
N-ethylmorpholine	100-74-3	20 ppm Skin[2] (OSHA)	NR	NR	5 ppm Skin1 (ACGIH)
Triethanolamine	102-71-6	NR	NR	NR	5 mg/m^3 (ACGIH)
Dimethylamino ethanol, 2-	108-01-0	NR	6 ppm (Ontario)	NR	3 ppm (Ontario)
N,N-Dimethylaminopropyl-amine	109-55-7	NR	NR	NR	0.5 ppm (ACGIH)
Diethanolamine	111-42-2	NR	NR	1 mg/m^3 (ACGIH)	3 ppm (ACGIH)
Triethylamine	121-44-8	25 ppm (OSHA)	3 ppm (ACGIH)	NR	NR
Triethylenediamine	280-57-9	NR	NR	NR	1 ppm Skin1 (Ontario)
Bis (2-Dimethylaminoethyl) ether	3033-62-3	NR	0.15 ppm Skin[1] (ACGIH)	NR	0.05 ppm Skin1 (ACGIH)

[1] Potential for significant contribution to overall exposure by skin.

[2] Substance that may be absorbed through the skin.

PEL = permissible exposure limits

STEL = short-term exposure limits

TWA = time-weighted average

TLV = threshold limit values

NR = Not reported

OSHA= Occupational Safety and Health Administration

ACGIH = American Conference of Government Industrial Hygienists

Ontario = Ontario Ministry of Labor in Canada

Reference (US Consumer Product Safety Commission, 2012): Status Report Staff Review of Five Amine Catalysts in Spray Polyurethane Foam.

6. Safer Alternatives to Spray Polyurethane Foam

Based on the increasing knowledge of the health risks and environmental impacts of SPF products and applications, several manufacturers are attempting to identify safer ways to produce and install insulation. Innovative engineering controls designed to reduce exposure in the workplace include the use of robots, mostly during SPF rooftop applications. In Europe, robot solutions are being implemented for building, maintenance, and upgrades in construction. The robots can enter crawl spaces and other areas where human access during application is hazardous.

Safer alternatives to conventional polyurethanes have been reported by in several publications *(Figovsky et al., 2013, Javni et al., 2008).* Advances in technology have allowed for the development of non-isocyanate polyurethane materials based on cyclic carbonate oligomers. Non-isocyanate polyurethane foams are obtained through the reaction between polycyclic carbonate oligomers and polyamines, which form polyhydroxy-urethane polymers. Figovsky et al. (2013) suggested that the production of the non-isocyanate polyurethanes is relatively safe for humans in comparison to the production of conventional polyurethanes. In 2015, Hybrid Coating Technologies/Nanotech Industries, California, received an award from the EPA for the Presidential Green Chemistry Challenge for designing the first hybrid non-isocyanate polyurethane, or "green polyurethane"; however, part A of this formulation contains skin irritants that can potentially cause allergic reactions upon exposure due to the similarity to isocyanates. Part B is moderately toxic with skin absorption and highly corrosive to the eyes, respiratory tract, gastrointestinal tract, and skin. The health effects of the part B ingredients of this green polyurethane formulation cannot be reviewed because the SDS sheets indicate that the ingredients are trade secrets.

Soy-based polyol alternatives have been promoted as "safer" and "green" because they are bio-based ingredients. Soy-based SPF is becoming more common among manufacturers as the information on SPF toxicity is made more publicly available. The percentage of soy within these SPF products is only around 10%-20% of the product. This type of SPF comes in both open and closed-cell forms, but it achieves a higher R-value compared to other SPFs on the market and uses less materials.

Substitution with safer products is a highly desirable exposure elimination or reduction strategy; however, using a different chemical or product does not necessarily mean it is safer. Insulation products that are green may still contain toxic chemicals with known adverse health effects or with limited toxicity data. While researching and developing safer alternatives is highly important, the focus on the safe use of existing spray polyurethane foam products remains essential to reduce or eliminate the risks.

Spray foam insulation is a good example of a high quality-insulating product that relies on isocyanates, one of the most potent chemical sensitizers known to man. While SPF can be used safely, its history of the past few decades illustrates the various challenges in maintaining a balance between product formulation and performance, raw material input and occupational health issues arising during its application. These aspects of product development and stewardship are important considerations in the sustainability efforts and require continuous attention, especially when new applications and or formulations enter the marketplace.

References

Bayer Material Science The chemistry of polyurethane coatings. A General Reference Manual.

Bello, D., Herrick, C. A., Smith, T. J., Woskie, S. R., Streicher, R. P., Cullen, M. R., Liu, Y. & Redlich, C. A. 2007. Skin exposure to isocyanates: reasons for concern. Environ Health Perspect, 115, 328-35.

Bello, D., Woskie, S. R., Streicher, R. P., Liu, Y., Stowe, M. H., Eisen, E. A., Ellenbecker, M. J., Sparer, J., Youngs, F., Cullen, M. R. & Redlich, C. A. 2004. Polyisocyanates in occupational environments: a critical review of exposure limits and metrics. Am J Ind Med, 46, 480-91.

Bilan, R. A., Haflidson, W. O. & Mcvittie, D. J. 1989. Assessment of isocyanate exposure during the spray application of polyurethane foam. Am Ind Hyg Assoc J, 50, 303-6.

Buyle, M., Braet, J. & Audenaert , A. 2013. Life cycle assessment in the construction sector : A review. Renewable and Sustainable Energy Reviews

Crespo, J. & Galan, J. 1999. Exposure to MDI during the process of insulating buildings with sprayed polyuretheane foam. . Ann Occup Hyg, 43, 415-419.

Doug Kramer September 2016. Spray Foam's Move Toward Sustainability And Why It Matters

Figovsky, O., Shapovalov, L., Leykin, A., Birukova, O. & Potashnikova, R. 2013. Recent advances in the development of non-isocyanate polyurethanes based on cyclic carbonates. PU Magazine.

Henriks-Eckerman, M. L., Makela, E. A., Laitinen, J., Ylinen, K., Suuronen, K., Vuokko, A. & Sauni, R. 2015. Role of dermal exposure in systemic intake of methylenediphenyl diisocyanate (MDI) among construction and boat building workers. Toxicol Lett, 232, 595-600.

Howard, H. P., Tunkel, J. L. & Banerjee, S. 1996. Identification of CFC and HCFC substitutes for blowing Polyurethane foam insulation products

Huang, Y. C. & Tsuang, W. 2014. Health effects associated with faulty application of spray polyurethane foam in residential homes. Environ Res, 134, 295-300.

IRS. 2016. https://www.irs.gov/uac/Energy-Incentives-for-Individuals-in-the-American-Recovery-and-Reinvestment-Act [Online]. [Accessed].

Javni, I., Hong, D. P. & Petrovic, Z. S. 2008. Soy-based polyurethanes by nonisocyanates route. Journal of Applied Polymer Science, 108, 3867-3875.

Kavanaugh, C. 2016. Home improverment projects drive sales of spray foam insulation Plastics News. Crain Communications Inc. .

Lesage , L., Stanley , J., Karoly , W. J. & Lichtenberg , F. W. 2007. Airborne Methylene Diphenyl Diisocyanate (MDI) Concentrations Associated with the Application of Polyurethane Spray Foam in Residential Construction. Journal of Occupational and Environmental Hygiene

Meier-Westhues , U. 2007. Polyurethanes

MichelottI, M. M., Gupta, C. & Hood, C. T. 2015. Persistent Amine Keratopathy Secondary to Indirect Exposure to Spray Polyurethane Foam Insulation. JAMA Ophthalmology.

OSHA 2013. A Guide to Occupational Exposure to Isocyanates. N.C. Department of Labor.

Redlich , C., Bello, D. & Wisnewski, A. 2006. Isocyanate exposures and health effects. Environmental and Occupational Medicine, 502-516.

Robert, A., Ducos, P., Francin, J. M. & Marsan, P. 2007. Biological monitoring of workers exposed to 4,4'-methylenediphenyl diisocyanate (MDI) in 19 French polyurethane industries. Int Arch Occup Environ Health, 80, 412-22.

Sonnenschein, M. F. 2014. Polyurethanes: Science Technology Markets and Trends, Wiley Series on Polymer Engineering and Technology.

SPFA 2012. Life Cycle Assessment of Spray Polyurethane Foam Insulation for Residential & Commercial Building Applications.

UNEP. 2016. http://www.unep.or.jp/ietc/Activities/Urban/sustainable_bldg_const.asp [Online]. [Accessed].

US Consumer Product Safety Commission 2012. Staff Review of Five Amine Catalysts in Spray Polyurethane Foam.

US EPA TTSCA Work Plan Chemical Problem Formulation and Initial Assessment. Chlorinated Phosphate Ester Cluster Flame Retardants. In: PREVENTION, O. O. C. S. A. P. (ed.).

US EPA 2011. Methylene Diphenyl Diisocyanate (MDI) And Related Compounds Action Plan

US EPA 2000. Ethylene Glycol.

US EPA. 2016. http://www.epa.gov/sites/production/files/2015-01/documents/spf_presentations.pdf [Online]. [Accessed].

USGBC. 2016. http://www.usgbc.org/articles/what-green-building [Online]. [Accessed].

WHO 1998. Flame retardants : Tris chloropropyl phosphate and tris 2-chloroethyl phosphate Geneva, 1998

Wisnewski, A. V., Liu, J. & Redlich, C. A. 2013. Connecting glutathione with immune responses to occupational methylene diphenyl diisocyanate exposure. Chem Biol Interact, 205, 38-45.

4. EVALUATING CLEANER PRODUCTION INTERVENTIONS IN A MEDIUM SIZE COMPANY

Biagio F. Giannetti, Cecilia Maria Villas Boas Almeida, Feni Dalano Roosevelt Agostinho, Jose Fernando Faro, Fabio Sevegnani

1. Introduction

Based on case studies in Brazil waste minimization programs and CP practices could generate promising results in reducing pollution at low costs (CETESB, 2002); however, medium-size industries are hindered from implementing the practices due to various attitudinal, organizational, technical, and economic barriers. In São Paulo, Brazil, educational initiatives that describe the environmental and financial benefits of CP are encouraged by CETESB (Environmental Sanitation Technology Company), which is the state environmental agency that monitors CP projects within companies and shares the data with other companies to explain the benefits (CETESB, 2002). Projects monitored by the CETESB have a good chance of success because companies that volunteer to participate can improve their environmental performance, increase innovation, and have access to the CETESB's advisors; however, several initiatives are still adopted without this type of support, resulting in improvements that are not properly documented and therefore do not effectively encourage companies to incorporate elements of CP in their routine procedures. Moreover, most large-scale industry reports remain unpublished due to confidentiality.

The adoption of environmentally sound technological solutions based on scientific research is another relevant strategy that should be addressed. To accomplish the necessary changes, academic results and insights can be integrated into the industry, and based on the sets of experiences, it would be easier to restructure concepts and principles. Most of the initiatives in Brazil regarding CP are still dependent on academic groups that share the concepts with their communities. The group from Paulista University promotes the International Workshop Advances in Cleaner Production every two years (www.advancesincleanerproduction.net). This multi/interdisciplinary forum was designed for the exchange of information and research results on technologies, concepts, and policies based on CP and was conceived to assist the desired transition to a sustainable society. This group has also developed a series of theses, dissertations, articles, and books on environmental concerns (Carvalho, 2015; Di Salvo, 2015; Oliveira, 2015; Lupinacci, 2015; Coelho, 2014; Tassinari, 2013; Mariano, 2013; Sevegnani, 2013; Demétrio, 2012; Di Augustini, 2012; Frugoli, 2012; Simões, 2012; Demétrio, 2011; Vendrametto, 2011; Frimaio, 2011; Ferreira, 2011; Lima, 2011; Faro, 2007; Giannetti et al., 2011a, 2011b, 2013a, 2013b, 2013c, 2015; Almeida et al., 2011, 2012, 2013a, 2013b, 2013c, 2015; Agostinho and Ortega, 2013; Agostinho and Siche, 2015; Agostinho et al., 2013, 2015; Mariano et al., 2015; Di Augustini et al., 2015; Frugoli et al., 2015; Frimaio et al., 2011; Giannetti and Almeida, 2006; Giannetti et al., 2016).

It is known that cleaner technologies and practices are diffusing comparatively slowly in general despite the benefits that have been documented in systems in which they have been implemented (Giorgio et al., 2009). It is also argued that the implementation of CP programs is no guarantee of continuity in environmental progress in itself unless management systems are used to ensure that the activities are continuous and systematic (Zwetsloot, 1995), and it is critical to measure the results of CP practices. Identifying appropriate indicators that address both the productivity and environmental aspects of a system is still a challenge. The indicators should not only enable the estimation of the CP practices suitable for a product or process and comparisons with other equivalents but also the quantitative measurement of improvements of the existing process or product, which would facilitate the development of new products.

In this context, the need for using appropriate methodological tools to correctly assess the real environmental costs and benefits of any practice, support decision making, and identify where improvements need to be made is acknowledged. The use of performance indicators within medium-size enterprises can help monitor and compare the environmental-economic improvements systematically as a first step toward a more complex evaluation; however, environmental-economic improvement is a rather general term that can include raw material and energy use, aspects that affect worker health and safety, discharges to air, water, and land, including solid waste for landfill disposal, and the environmental impact of products during use and disposal (Roberts, 1996). Thus, there are several approaches to determining the optimum level between economic and environmental aspects. One is to perform an impact assessment to evaluate the most environmentally benign system among the design alternatives (Shonnard and Hiew, 2000; Nielsen and Wenzel, 2002). A second approach is based on process integration methodologies for final comparative assessments (Bagajewicz, 2000; Rossiter and Kumana, 1995; Alva-Arga̕ez et al., 1998; Telukdarie and Haung, 2006; Erol and Thorming, 2005).

The present chapter analyzes the use of resources in a non-cyanide alkaline industrial system with chromate conversion coating located in São Paulo, SP,Brazil. The process change to the organo-metallic technology aims to provide environmental benefits due to the non-use of chrome. To assess the potential technology change, emergy accounting was used for a quantitative environmental assessment to compare two different processes used for metal fastener coating. The emergy corresponding to the damage to human health or the number of years of life lost due to the emission of chromium to water was also evaluated.

A case study that describes the experiences of a medium-size company that adopted different CP concepts as tools for environmental management in a joint action with the researchers of Paulista University is presented. CP concepts were used to achieve the reduction or elimination of hazardous materials used as raw materials for the production process. In addition, the changes in the input materials would also eliminate the generation of hazardous waste during the production process. Due to the need to substitute the toxic input by imposition of the costumers, the company intended to apply CP concepts to replace the existing technology. Technology change is a well-known strategy used by CP practitioners, and it refers to modifications in the process and/or equipment to increase production efficiency and reduce waste and emissions. These changes can range from small, low-cost options to the replacement of processes that involve large capital investments. A technology assessment was conducted using emergy accounting to evaluate the efficiency and the disavantages of each technology. An evaluation of the environmental services used to dilute the release of toxic substances in the effluent was also performed.

An example of the application and evaluation of CP options (good operational practices, material and raw material changes, technological modifications, and product change) is presented to motivate product manufacturers to prioritize environmental performance and assessments and their products and services equally as well as to save manufacturers substantial time and efforts during their first attempts to implement CP actions.

2. Emergy Accounting

Emergy accounting was used to evaluate the company in the case study, as it provides strong scientific-based indicators that can assess several aspects of the company's performance.

Emergy is the available energy of one kind previously used up directly and indirectly to make a service or product. Its unit is the solar emergy joule, sej. (Odum, 1996). Emergy's logic of memorization rather than conservation is different from other energy-based analyses (Brown and Herendeen, 1996). An emergy synthesis separates renewable (R) from non-renewable inputs (N) and local (I = N + R) from external inputs (F). These distinctions allow for defining several emergy-based indicators that can support decision making (Brown and McClanahan, 1996) (Figure 4.1).

Emergy indicators (unit emergy value [UEV]) and emergy yield ratios (EYR) include the aspects of environmental sustainability issues regarding resource use, its origin, and process efficiency in converting inputs into outputs. The total emergy per unit of product or service (UEV expressed in sej/unit) is a measure of global efficiency. The less emergy needed to produce a given amount of product, the more efficient (in relation to the biosphere) the system will be.

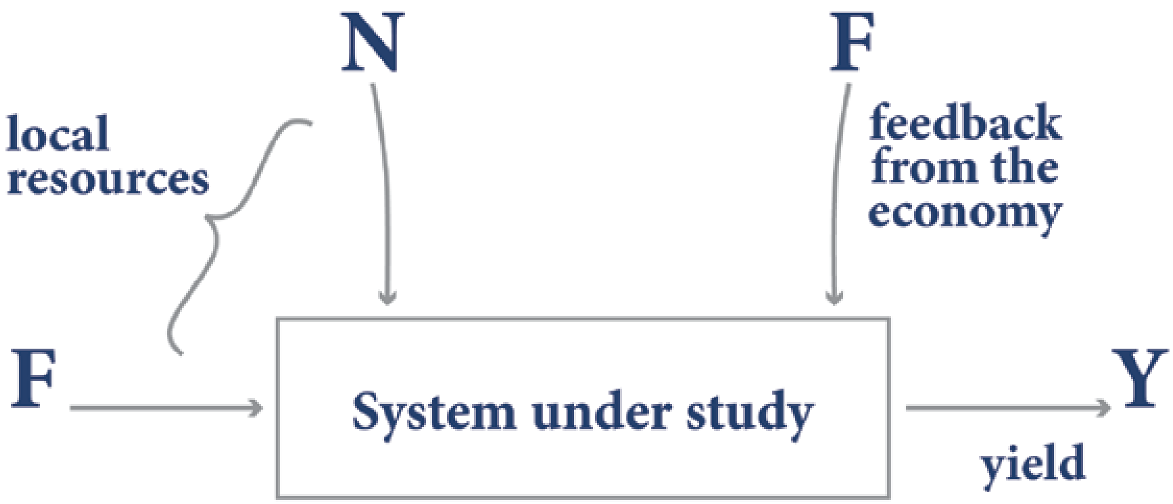


Figure 4.1 Three Arm Energy System Diagram. R (renewable resources), N (non-renewable resources), F (feedback from the economy), Y (yield).

EYR is the ratio of total emergy (Y = R + N + F) to the emergy purchased from the market (F). This index shows the efficiency of the system in the use of the available local resources.

Emergy accounting allows for the conversion of all contributions received by the production system (metals, energy, oil, money, and even information) on a single basis of measurement: the solar energy joule (sej). Systems under study can be compared regarding efficiency in resource use, productivity, environmental burden, and global sustainability.

The evaluation procedure applied is performed according to the following steps:

- Definition of the system under study to set the boundaries for investigation;
- Study of the context in which the system is inserted and execution of the mass balance;
- Elaboration of energy flow diagrams;
- Elaboration of emergy tables with data collected;
- Emergy Indicators Calculation;
- Discussion for future management actions and decision-making.

3. The Case Study of the Medium-Size Metal-Finishing Company

The application of sacrificial coatings onto steel and other ferrous substrates has long been established as an effective and reliable standard of the industry for corrosion protection. Due to its low cost, zinc has been used as the predominant coating. Approximately 30% of the zinc used by the automotive industry is used for coatings, which allows manufacturers to warranty their vehicles up to 12 years against corrosion. In 1996, 494,000 metric tons were used by the automotive industry globally, which was 6.6% of 1996's total global zinc consumption (Johnston, 1999).

The application of zinc electroplating is evident in everyday life and ranges from cars to the fasteners that hold their parts together. The automotive and fastener industry are two of the largest consumers of zinc electroplated goods (Johnston, 1999).

Most developments in this area focused on improving corrosion resistance and process optimization (Chettry, 1999). There are several different processes available for the electrolytic application of zinc. The zinc cyanide system was the original process used to electroplate zinc; however, these systems are being replaced with the advent of alternatives that avoid the use of hazardous substances, such as cyanides. Acidic chloride-based zinc plating processes provide brightness that competes with nickel-chrome plating, and they are quite conductive, leading to high plating efficiency, which saves energy and increases productivity. Sulfate-based systems also operate at acidic pH and are employed when a bright deposit is not required. There is also a non-cyanide alkaline version of zinc plating that is used, especially in the fasteners industry.

The corrosion resistance of plated zinc is enhanced by treating it with a conversion coating, which can remarkably increase its corrosion resistance. These conversion coatings are applied to zinc-plated surfaces through immersion in solutions containing chromate or dichromate ions. Another benefit of conversion coating is that it will give the article color, from an almost colorless to blue to yellow, green, and black. Yellow conversion coatings are popular due to their ability to resemble brass and can be found on all types of fasteners.

Environmental aspects of the zinc plating industry, as well as the metal finishing industry in general, have been a focus of attention, such as the development of low-wastewater discharge systems (Cohen and Overcash, 1995). Environmental issues associated with Cr(VI) are well-documented, and the search for alternatives is the subject of extensive research and development in the zinc-plating industry (Hadley et al., 2002); however, several commercial systems still employ conversion coatings based on hexavalent chromium salts to achieve the desired corrosion resistance.

Recently, organo-metallic coatings were suggested by the automotive industry as an environmentally friendly solution to replace zinc-coating processes and as an alternative to avoid the harmful consequences related to the use of conversion coatings based on Cr(VI). The technology for organo-metallic coatings was developed in the U.S. in the mid-1960s. The company responsible for this development, which is now part of a large chemical conglomerate, was originally known as Diamond Shamrock Co. In the early 1990s, Geomet water-based technology and Zintek solvent-based technology was provided to the market. It should be noted that there is a lack of relevant scientific publications in relation to organo-metallic coatings because both are patented products, and such technology is held by few companies.

In 2007, the company in study expressed a strong wish to replace the zinc-coating process with an organo-metallic process. The process currently used by the company is the electroplating bath with alkaline cyanide-free zinc deposition process and a conversion layer that uses Cr(VI). The company intends to gradually substitute the current process with the water-based organo-metallic coating process (Geomet).

4. Emergy Accounting for the Medium-Size Metal-Finishing Company in the Case Study

The company in study evaluated the supplies of the automotive industry in São Paulo, Brazil, and it produces nearly 120 tons of zinc-plated fasteners each month. The data collected refers to the company's production in 2005.

The energy system diagrams illustrated in Figures 4.2 and 4.3 were designed to combine information about the systems of interest from various sources and to organize efforts for data gathering. The diagrams show all material and energy flows circulating in both production systems as well as the systems' interactions with the environment. All driving energies from the external economic system (larger economy), the environment, and interactions are included (Odum, 1996). On the left side of the diagram, renewable resources (R) are represented, purchased or imported resources (F) are at the top, and the yield of the system (Y) is represented on the right side, which is the coated fasteners in this case. The diagrams were used to analyze tables of data required for emergy accounting.

As shown in Figure 4.2, the zinc-coating process has an effluent treatment unit (ETU), which feeds part of the water treated back into the production process. The sludge produced in the ETU is sold to the ceramic industry. The organo-metallic coating process also has an ETU, but the water is directly rel eased to the environment after treatment. The sludge is sold to the ceramic industry.

Tables 4.1 and 4.2 show all inputs needed for system implementation divided by plant lifetime, annual operating inputs (labor, electricity, machinery, human services), and direct and indirect environmental inputs (water). Suitable UEVs were assigned that resulted in the emergy values in sej after being multiplied by the energy inputs. During the implementation phase, steel was considered a resource from the economy (F) to be incorporated in the equipment purchased from third parties or in the facility structure. On the other hand, the steel used for the operation was considered a non-renewable resource (N). The water used in the system was taken from an artesian well and was considered a non-renewable resource (N) because the ground water in the city of São Paulo is used faster than its recovery time (Milaré, 1991).

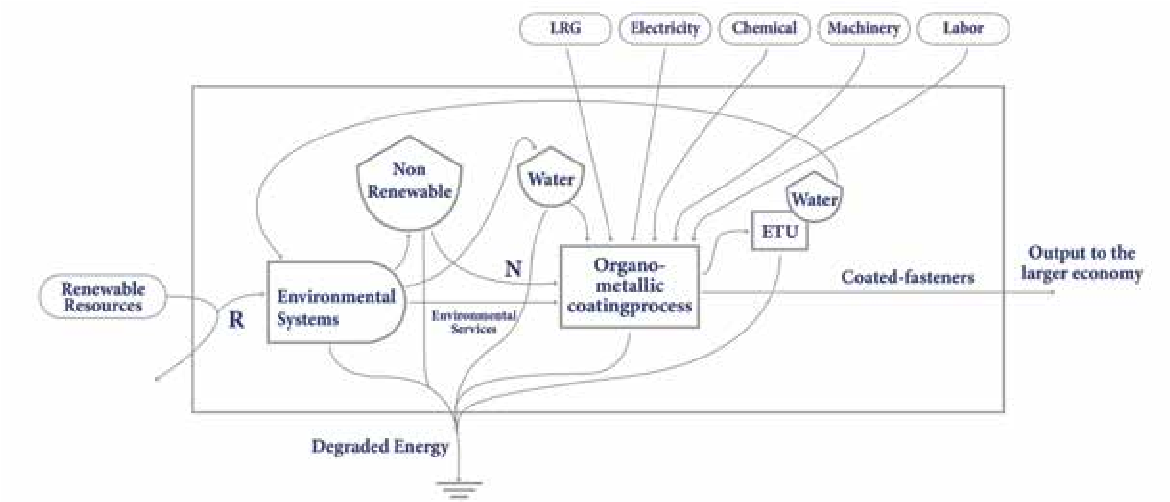


Figure 4.2 Energy System Diagram of the Zinc-Coating Process

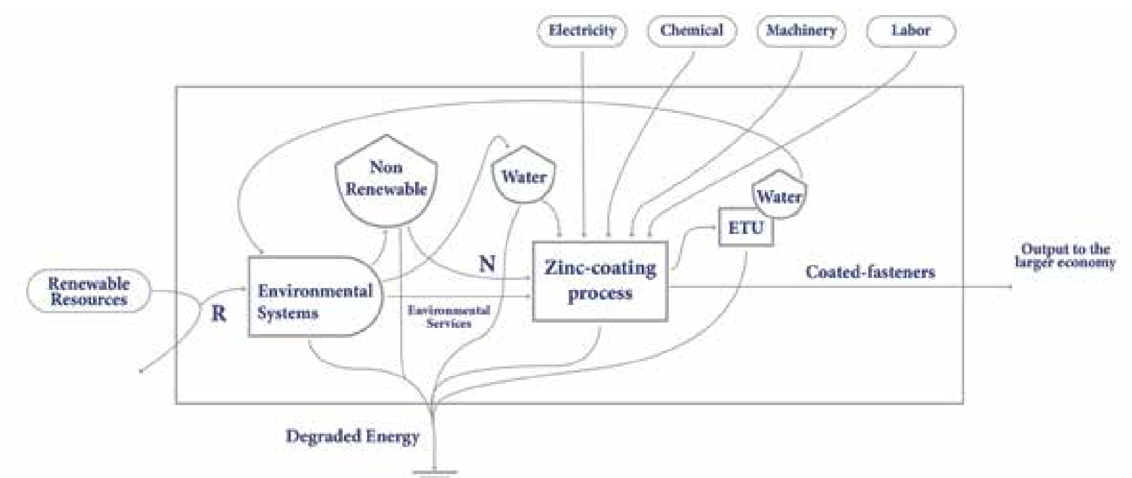


Figure 4.3 Energy Diagram of the Organo-Metallic Coating Process.
LPG refers to Liquid Petroleum Gas.

Table 4.1 shows the flows of materials and energy required for the zinc-coating system. The emergy involved in the coating process as well as the emergy of the coated fasteners were calculated. Column (a) shows the percentage of each item in relation to the total coating process emergy (Y1), while column (b) shows the percentage values corresponding to the total emergy of the coated fasteners (Y2).

In the zinc-coating process, the highest values of emergy are associated with electricity (49%), labor (25%), and chemicals (15%) (column a). Column b of the table shows the steel used to make the fasteners, and the percentages drop to 4% for electricity, 2% for labor, and 1% for chemicals, while 92% of the total emergy corresponds to the steel used to make the fasteners.

The water fed back by the ETU corresponds to 31% of the weight of total water use. Thus, it would be reasonable to suppose that the savings related to its use would also correspond to environmental benefits. In fact, if there were no water reuse, a quantity of 8.4 x 108 g/year could be added to the water input, leading to an emergy contribution of 1.89 x 1014 sej/year to the total emergy of the zinc-plating process; however, as the contribution of water inflow represents only 0.5% sej/sej of the total emergy of the zinc-plating process, this value is not relevant enough to change the UEV of the process, that is, its efficiency.

Table 4.1 Material and energy flows for the zinc-coating process

Description		Unit	Class	Value	UEV (sej/un)	Emergy (sej/year)	% (sej/sej)	% (sej/sej)
							(a)	(b)
Implantation								
1	Concrete	g	F	5.94 x 10^6	1.54 x 10^9	9.15 x 10^{15}	5.55%	0.42%
2	Steel	g	F	1.60 x 10^6	2.77 x 10^9	4.43 x 10^{15}	2.68%	0.21%
3	Polypropylene	g	F	1.37 x 10^5	5.87 x 10^9	8.04 x 10^{14}	0.49%	<0.10%
4	Equipment	g	F	5.30 x 10^4	4.10 x 10^9	2.17 x 10^{14}	0.13%	<0.10%
5	Labor	J	F	5.02 x 10^7	4.30 x 10^6	2.16 x 10^{14}	0.13%	<0.10%
6	Machinery	g	F	2.22 x 10^4	4.10 x 10^9	9.10 x 10^{13}	<0.10%	<0.10%
7	PVC	g	F	1.15 x 10^4	5.87 x 10^9	6.75 x 10^{13}	<0.10%	<0.10%
8	Water	g	N	2.70 x 10^7	2.25 x 10^5	6.08 x 10^{12}	<0.10%	<0.10%
9	Rubber	g	F	1.00 x 10^3	4.30 x 10^9	4.30 x 10^{12}	<0.10%	<0.10%
Operation								
10	Electricity	J	F	4.95 x 10^{11}	1.65 x 10^5	8.17 x 10^{16}	49.52%	3.78%
11	Labor	J	F	9.80 x 10^9	4.30 x 10^6	4.21 x 10^{16}	25.52%	1.95%
12	Chemicals	g	F	2.55 x 10^7	1.00 x 10^9	2.55 x 10^{16}	15.45%	1.18%
13	Water	g	N	3.67 x 10^9	2.25 x 10^5	8.26 x 10^{14}	0.50%	<0.10%
	Emergy (process)	kg	Y1	7.2 x 10^3	2.29 x 10^{13}	1.65 x 10^{17}	100.00%	--
14	Steel	g	N	7.20 x 10^8	2.77 x 10^9	1.99 x 10^{18}	--	92.13%
	Emergy (fasteners)	kg	Y2	7.27 x 10^5	2.97 x 10^{12}	2.16 x 10^{18}	--	100.00%

(a) considering items from 1 to 13; (b) considering items from 1 to 14.

The influence of the water inflow on the total emergy of the zinc-plated fasteners is even lower at 0.10% sej/sej. Thus, despite an undeniable benefit of saving 840 m^3 of a non-renewable resource, this percentage is insufficient to improve the environmental efficiency of the process, and the use of the main inflows (electric energy, chemicals, and man labor) should preferentially be focused on other alternatives.

Table 4.2 shows the flows of materials and energy that contribute to the organo-metallic coating system. Data were provided by one of the largest Brazilian users of organo-metallic coatings, which has a unit capable of producing about 60 t/month of coated fasteners.

In Table 4.2, the emergy required by the organo-metallic coating process as well as the total emergy required by the coated fasteners are calculated. In the coating process, the highest values of emergy are related to electricity (44%), liquid petroleum gas LPG (33%), labor (17%), and chemicals (4%) (column a). Column (b) includes the number of produced fasteners, and the percentages are 10% for electricity, 7% for LPG, 4% for labor, and 1% for chemicals. The steel used to manufacture the fasteners corresponds to 78% of the total emergy.

Table 4.2 Material and energy flows for the organo-metallic coating process

Description		Unit	Class	Value	UEV (sej/un)	Emergy (sej/year)	% (sej/sej)	% (sej/sej)
							(a)	(b)
Implantation								
1	Concrete	g	F	3.50×10^6	1.54×10^9	5.39×10^{15}	0.96%	0.21%
2	Equipment	g	F	5.58×10^5	4.10×10^9	2.29×10^{15}	0,41%	<0.10%
3	Steel	g	F	2.00×10^5	2.77×10^9	5.54×10^{14}	0,10%	<0.10%
4	Machinery	g	F	1.10×10^5	4.10×10^9	4.51×10^{14}	<0.10%	<0.10%
5	Labor	J	F	5.02×10^7	4.30×10^6	2.16×10^{14}	<0.10%	<0.10%
6	Rubber	g	F	5.00×10^4	4.30×10^9	2.15×10^{14}	<0.10%	<0.10%
7	Polypropylene	g	F	2.00×10^4	5.87×10^9	1.17×10^{14}	<0.10%	<0.10%
8	Water	g	N	3.50×10^6	2.25×10^5	7.88×10^{11}	<0.10%	<0.10%
Operation								
9	Electricity	J	F	1.50×10^{12}	1.65×10^5	2.48×10^{17}	43.97%	9.69%
10	PLG	J	F	3.89×101^2	4.80×10^4	1.87×10^{17}	33.16%	7.30%
11	Labor	J	F	2.29×101^0	4.30×10^6	9.85×10^{16}	17.46%	3.85%
12	Chemicals	g	F	2.20×10^7	1.00×10^9	2.20×10^{16}	3.90%	0.86%
13	Water	g	N	2.64×10^8	2.25×10^5	5.94×10^{13}	<0.10%	<0.10%
	Emergy (process)	kg	Y1	3.00×10^3	1.88×10^{14}	5.64×10^{17}	100.00%	--
14	Steel	g	N	7.20×10^8	2.77×10^9	1.99×10^{18}	--	77.73%
	Emergy (fasteners)	kg	Y2	7.23×10^5	3.54×10^{12}	2.56×10^{18}	--	100.00%

Table 4.3 summarizes the results of both processes and shows that less emergy is required by the zinc-coating process. That is, fewer resources are used to obtain fasteners using this process. The organo-metallic coating has a total emergy of about eight times higher than the zinc-coating process in producing 1 kg of coated-fasteners, and the fasteners obtained through this process use about 19% more resources per year than zinc-coating.

Table 4.3 Total emergy used to produce zinc-coated and organo-metallic coated fasteners

	Zinc-coating	Organo-metallic coating
for the process		
Emergy / (x 10^{17} sej/year)	1.65	5.64
UEV (x 10^{13} sej/kg)	2.29	18.80
for the fasteners		
Emergy / (x 10^{17} sej/year)	21.60	25.60
UEV / (x 10^{13} sej/kg)	0.29	0.35

5. Evaluating the Implementation of the Organo-Metallic Process at the Company

The company aims to implement the organo-metallic process in combination with the zinc-coating process to comply with the needs of all customers. The aim of the initial project was to produce 45 tons of zinc-coated fasteners and 60 tons of organo-metallic fasteners monthly.

5.1. Emergy Efficiency (UEVs) Calculation

For the evaluation of each process, 727,200 kg/year of zinc-coated fasteners (Table 4.1) and 723,000kg/year of organo-metallic coated fasteners (Table 4.2) were considered in the emergy accounting. For project implementation, the quantity of zinc-coated fasteners equalled 545,400 kg/year, and the quantity of organo-metallic coated fasteners equalled 723,000 kg/year. Table 4.4 shows the UEVs for each process.

Table 4.4 Emergy and UEVs for the zinc-coated fasteners, the organo-metallic coated fasteners, and the combination of both processes (Project)

	Zinc-coated (Table 4.3)	Organo-metallic coated (Table 4.3)	Project
Emergy / (sej/year)	2.16 x 10^{18}	2.56 x 10^{18}	4.64 x 10^{18}
UEV / (sej/kg)	2.97 x 10^{12}	3.54 x 10^{12}	3.65 x 10^{12}

Table 4.4 shows that the zinc-coated fasteners' UEV is lower than that of the organo-metallic coatings, and it is also lower than that relative to the fasteners produced by the company if the processes were used simultaneously. The results obtained show that regarding the use of resources, it is more advantageous (i.e., higher global efficiency) to maintain the zinc-coating process technology.

5.2. Emergy Indices Calculation

Once the total number of input flows to the coating processes has been identified and the total emergy driving the processes has been calculated, a set of indices and ratios can be calculated. These indices have been shown to be particularly useful when studying processes under human control where a sustainable pattern is not guaranteed and choices must be supported by the careful consideration of several different parameters.

For systems that lack the use of renewable resources, the emergy yield ratio (EYR) and the emergy investment ratio (EIR) can be calculated, while the ESI and ELR cannot. These indices provide important information about a system's contribution to the economy (EYR) and its efficiency in the use of local resources (EIR). Table 4.5 shows the calculated indices for the coated fasteners for both processes separately and if the project were to be implemented by the company.

Table 4.5 Emergy indices for the coated fasteners produced by the zinc-coating process, organo-metallic coating process, and produced by the company, which includes with both processes (Project)

Emergy indices	Zinc-coated (Table 4.1)	Organo-metallic coated (Table 4.2)	Project
Emergy yield ratio (EYR*)	13.14	4.54	4.05
Emergy Investment ratio (EIR*)	0.08	0.28	0.33

* EYR = Y/F ; EIR = F/(R+N)

Table 4.5 shows that the EYR of the zinc-coated fasteners equals 13, meaning that the zinc-coating process returns 13 times the investment to the economy, while the process of organo-metallic coating aggregates 4.5 times more emergy to the local economy. The higher the value of this index, the greater the return obtained per unit of emergy invested. In the combined process planned by the company, there would be an emergy increase of four times the investment.

Regarding EIR, the less the ratio, the less the economic costs. It can be observed that the emergy investment of the zinc-coating process is the lowest among the three alternatives, indicating a higher usage of natural resources.

6. Extending the Evaluation beyond the Borders of the Company: The Emergy Invested by the Environment to Manage the Chromium Contained in the Effluent

It is worth noting that the organo-metallic coatings were suggested by the automotive industry as an environmentally friendlier solution to replace the zinc-coating processes. The major advantage is associated with the lack of chromium in the effluents of the production process.

Although the calculation of the UEVs is indicative of the efficiency of a process, it is insufficient in determining whether a case is more beneficial than another, especially when other factors influence the conclusion. Thus, the environmental benefit related to the application of organo-metallic coatings that was disregarded by the calculation of UEVs was evaluated.

Environment services that naturally treat effluents include the removal and immobilization (even bioaccumulation) of substances and the response of the environment to toxicity. Once emitted to the environment, all substances may be diluted by ecosystem services, such as wind and water flows, to a local concentration. Several factors, such as spatial and temporal dispersion, diffusion, and atmospheric chemistry, are crucial in the determination of the local concentration. If the concentration of the substance emitted is greater than the local concentration value, the emission will cause harm to humans and to the ecosystem. The damage itself is therefore dependent on the existence of pollutants in the ecosystem and on human exposure to the pollutants.

The amount of chromium present in the effluents generated by the zinc-coating process was used to calculate the response to the toxicity of the effluent and the energy used for its dilution. To assess the impacts to human health and to aggregate the effects of chromium emissions by the zinc-coating process, the DALY for hexavalent chromium emission to water (Disability Adjusted Life Years) was used (Goedkoop and Spriensma, 1999). The company's self-monitoring report indicated that the chromium concentration was below 0.01 mg/L (Review Report No. 6321 of 02.21.2006 issued by Centralsuper Commerce Chemicals Ltd.), which is the limit for disposal according to current Brazilian law.

The Effluent Treatment Unit (ETU) discards 4,000 liters of water per hour, and the zinc-coating process discards treated water for two hours daily for approximately 22 working days per month. The amount of chromium was calculated to be 0.02112 kg/year.

Equation 3 was used to calculate the emergy related to damage to human health. The calculated value (1.12×10^{14} sej / year) represents the emergy cost due to the chromium emission in its hexavalent form in the effluent (Genoni et al., 2003). This cost represents the response of the environment to the toxicity of the discharged effluent.

Taking both the dilution of substances in the physical environment and their processing by living organisms into account, Genoni et al. (2003) estimated the UEVs of several elements, including chromium. The chemical energy used to dilute the substances was considered to be at least equal to the Gibbs free energy associated with the gradient concentration between the effluent and the receiving environment (Equation 3).

$$E = N \times R \times T \times \ln C1/C2 \qquad (3)$$

Where:

N = number of moles of chromium discharged

R = universal gas constant (8.314 J / mol K)

Temperature T = 298K

C1 = concentration of the effluent discharged

C2 = the local concentration of the substance of interest

E = energy of the damage

The local concentration used (0.005 mg/L) refers to the concentration of chromium in urban areas because the company is located in Diadema, Brazil (Silva and Pedrozo, 2001). Thus, for 2.11×10^{-2} kg/year (0.41 mol/year), the chemical energy for the dilution of 0.01 mg/L is 704 J/year. To calculate the emergy invested from the environment in the dilution of chromium in the effluent, the energy value was multiplied by the UEV for the dilution (1.99×10^{10} sej/J) of the hexavalent chromium that was calculated by Genoni et al. (2003). Table 4.6 shows the total emergy invested by the environment to manage the chromium discarded by the zinc-coating process.

Table 4.6 Emergy related to chromium discharge by the zinc-coating process

Description	Class	Emergy / (sej/year)	% (sej/sej)
Zinc-coating process	Y1	1.65×10^{17}	99.92%
Emergy to respond to toxicity	R	1.12×10^{14}	0.07%
Emergy for dilution	R	1.40×10^{13}	0.01%
Total	Y1	1.65×10^{17}	

Table 4.6 includes the emergy invested by the environment to respond to the toxicity of the chromium released and to dilute it in water bodies. The results show that the total emergy investment is basically unchanged. This indicates that the concentration of chromium present in the effluent

must be close to that of the local concentration and that the treatment of the liquid effluent, which complies with the law, is efficient for minimizing the work and the response of the biosphere. The calculation of emergy invested by the environment to manage the maximum amount discarded in wastewater showed that the value used by the environment to dilute the toxicity was lower than 0.1% of the emergy demanded in the coating process.

It should be noted that this evaluation does not consider some important aspects. First, the calculations proposed by Ukidwe and Bakshi (2004) and Genoni et al. (2003) do not consider the accumulation of chromium in the water bodies, which should increase the value of the energy for dilution and the damage to human health, as it reduces the processing capacity of living organisms as a function of time. Similarly, this calculation does not consider the limits of receiving these annual amounts of chromium for the environment. It is known that in water bodies in rural areas, for example, the chromium concentration is no more than 5.00 x 10-6 mg/L (Silva and Pedrozo, 2001); however, using this value as the local concentration base will increase the emergy for dilution to 1.54 x 1014 sej/year, and it still represents no more than 0.1% of the total emergy of the zinc-coating process.

7. Discussion

Emergy accounting was used to evaluate the environmental performance of the manufacturing process of coated fasteners.

Considering only the use of resources to obtain the same amount of product, the methodology indicated that it is best to maintain the zinc-coating process. The calculation of the UEVs showed that regarding the use of resources, the zinc-coating process technology is more efficient in converting global resources into products.

Fasteners coated by the zinc-coating process contribute more to the economy (EYR = 13) than the organo-metallic coating process (EYR = 4.5). For the combination process proposed by the company, there would be an increase of four times the emergy, from 2.56 x 10^{18} sej/year to 4.64 x 10^{18} sej/year.

The emergy investment is about 3.5 times higher for the organo-metallic coating process when compared to the zinc-coating process, which indicates a better use of resources supplied by the economy by the zinc-coating process.

The calculation of environmental services to assessthe toxicity of chromium in the effluent and its dilution in water bodies showed that the effluent treatment is efficient and that the emergy invested by the environment to manage the amount discarded is lower than 0.1% of the emergy used in the coating process.

8. Conclusion

This chapter has described the experiences of a medium-size company that adopted different CP concepts as an approach to environmental management in a joint action with the researchers of Paulista University. Due to pressure from its clientele, this company conducted an evaluation to determine whether a change in process technology would be beneficial. Emergy indicators in combination with a health loss indicator (DALY) were employed for the quantitative measurements.

The decision to implement either low-cost or high-cost interventions depends on the specific goals of the individual establishment; however, there are rewards that worth when the intervention has a low cost. While good management practices would focus on bringing the production process performance to the designed level, small investments in CP actions may considerably improve environmental performance. The evaluation presented in this chapter shows that a quantitative assessment is imperative to corroborate decision making. Despite the advantages that were offered by suppliers regarding the elimination of chromium, it was clear that the change in technology would lead to a decrease in global efficiency or to an increase in the use of resources. This increase in resources used would be higher than the environmental services saved with the avoidance of the toxic release.

9. Acknowledgments

The authors thank the owners Irmãos Parasmo S.A. for the data supplied and their friendly cooperation. Special thanks are given to the staff of the company for keeping records of the key parameters, which allowed for this chapter to be written. This study received financial support from Vice-Reitoria de Pós-Graduação e Pesquisa da Universidade Paulista signatory of The International Declaration on Cleaner Production, a voluntary but public statement of commitment to the strategy and practices of cleaner production.

References

Agostinho F., Ortega, H., 2012. Energetic-Environmental Assessment of a Scenario for Brazilian Cellulosic Ethanol. Journal of Cleaner Production, 47, 474-489.

Agostinho F., Almeida, C. M. V. B., Bonilla, S. H., Sacomano, J. B., Giannetti, B. F., 2013. Urban solid waste plant treatment in Brazil: Is there a net emergy yield on the recovered materials? Resources, Conservation and Recycling, 73, 143-155.

Agostinho F., Siche, R., 2014. Hidden costs of a typical embodied energy analysis: Brazilian sugarcane ethanol as a case study. Biomass and Bioenergy, 71, 69-83.

Agostinho, F., Bertaglia, B. B. A., Almeida, C. M. V. B., Giannetti, B. F., 2015. Influence of cellulase enzyme production on the energetic–environmental performance of lignocellulosic ethanol. Ecological Modelling, 315, 46-56.

Almeida, C. M. V. B., Frimaio, G. S., Bonilla, S. H., Silva, C. C., Giannetti, B. F., 2011. Contabilidade Ambiental em Emergia de Projeto de Compensação Ambiental Ecoíris. Revista RACEF – Revista de Administração, Contabilidade e Economia da FUNDACE, Edição 04/2011.

Almeida, C. M. V. B., Bonilla, S. H., Giannetti, B. F., Frimaio, G. S., Silva, C. C., 2012. An Evaluation of an MSW-to-energy System Using Emergy Synthesis. International Journal of Environment and Sustainable Development, 11(3), 258-273.

Almeida, C. M. V. B., Madureira, M. A., Giannetti, B. F., Bonilla, S. H., 2013a. Substituição das soldas estanho-chumbo na manufatura: efeitos na saúde do trabalhador e no desempenho ambiental. Gestão & Produção, 20(1).

Almeida, C. M. V. B., Santos, A. P. Z., Bonilla, S. H., Giannetti, B. F., Huising, D., 2013b. The roles, perspectives and limitations of environmental accounting in higher educational institutions: an emergy synthesis study of the engineering programme at the Paulista University in Brazil. Journal of Cleaner Production, 52, 380-391.

Almeida, C. M. V. B., Madureira, M. A., Bonilla, S. H., Giannetti, B. F., 2013c. Assessing the Replacement of Lead in Solders: Effects on Resource use and Human Health. Journal of Cleaner Production, 47, 457-464.

Almeida, C. M. V. B., Carvalho N., Agostinho F., Giannetti, B. F., 2015. Using Emergy to Assess the Business Plan of a Small Auto-Parts Manufacturer in Brazil. Journal of Environmental Accounting and Management. 3, 371-384.

Alva-Argaez, A., Kokossis, A. C., Smith, R., 1998. Wastewater minimization of industrial systems using an integrated approach. Comput. Chem. Eng. 22, 741-744.

Bagajewicz, M. A., 2000. Rreview of recent design procedures for water networks in refineries and process plants. Comput Chem. Eng. 24, 2093-2099.

Brown, M. T., Herendeen, R. A., 1996. Embodied energy analysis and EMERGY analysis: a comparative view. Ecological Economics. 19, 219-235.

Brown, M. T., McClanahan, T. R., 1996. EMergy analysis perspectives of Thailand and Mekong River dam proposals. Ecological Modeling. 91, 105-130.

Carvalho, N., 2015. Contabilidade Ambiental de uma Pequena Empresa Fabricante de Autopeças do Estado de São Paulo. Master Thesis. Universidade Paulista-UNIP, Programa de Pós-Graduação em Engenharia de Produção, São Paulo, Brazil.

CETESB, Companhia de Tecnologia de Saneamento Ambiental. Jun 1998/2002. Manuais Ambientais CETESB, Projeto Piloto de Prevenção à Poluição. Casos de sucesso – São Paulo, Brazil.

Coelho, R. C. M., 2014. Contabilidade Ambiental e Econômica da Redução no Consumo de Água Potável e do Uso de Água de Chuva na Subprefeitura Capela do Socorro - São Paulo. Master Thesis. Universidade Paulista-UNIP, Programa de Pós-Graduação em Engenharia de Produção, São Paulo, Brazil.

Cohen, H. E. A., Overcash, M. R., 1995. Net-waste-reduction analysis applied to zero-water discharge systems for chromic acid electroplating, Journal of Cleaner Production. 3, 161-167.

Chettry, R., 1997. Record-Keeping Requirements Under Title V for Electroplating and Painting Facilities. Metal Finishing. 95, 45-51.

Demétrio, J. C. C., 2012. Avaliação Ambiental da Construção de Edificações de Interesse Social no Brasil. Doctorate Dissertation. Universidade Paulista-UNIP, Programa de Pós-Graduação em Engenharia de Produção, São Paulo, Brazil.

Demétrio, F. J. C., 2011. Avaliação de Sustentabilidade Ambiental do Brasil com a Contabilidade em Emergia. Doctorate Dissertation. Universidade Paulista-UNIP, Programa de Pós-Graduação em Engenharia de Produção, São Paulo, Brazil.

Di Augustini, C. A., Almeida, C. M. V. B., Agostinho F., Giannetti, B. F., 2015. Avaliação de impacto da escala econômica na dimensão ambiental das empresas do ISE da BM&FBOVESPA conforme parâmetros da Política Nacional do Meio Ambiente (Lei nº 10.165). Gestão & Produção, 22(1).

Di Augustini, C. A., 2012. Contribuição para Ranqueamento Setorial da Dimensão Ambiental do ISE da BM&FBOVESPA. Doctorate Dissertation. Universidade Paulista-UNIP, Programa de Pós-Graduação em Engenharia de Produção, São Paulo, Brazil.

Di Salvo, A. A., 2015. Avaliação Energético-Ambiental de Data Centers: Computação Tradicional versus Computação nas Nuvens. Master Thesis. Universidade Paulista-UNIP, Programa de Pós-Graduação em Engenharia de Produção, São Paulo, Brazil.

Erol, P., Thorming, J., 2005. ECO-design of reuse and recycling networks by multi-objective optimization, Journal of Cleaner Production. 13, 1492-1503.

Faro, J. F., 2007. Contabilidade ambiental aplicada a processos de revestimento de zinco e organo metálico em fixadores metálicos: Um estudo de caso. Master Thesis. Universidade Paulista-UNIP, Programa de Pós-Graduação em Engenharia de Produção, São Paulo, Brazil.

Ferreira, P. J. G., 2011. Estudo de Estações de Tratamento de Água a partir da Síntese em Emergia. Master Thesis. Universidade Paulista-UNIP, Programa de Pós-Graduação em Engenharia de Produção, São Paulo, Brazil.

Frimaio, G. S., Almeida, C. M. V. B., Giannetti, B. F., Bonilla, S. H., 2011. Aproveitamento dos Resíduos Sólidos Urbanos em Aterro Sanitário. Revista Agrogeoambiental, 3(1), 93-100.

Frimaio, G. S., 2011. Aterro Sanitário São João: Estudo dos Indicadores Ambientais em Emergia. Master Thesis. Universidade Paulista-UNIP, Programa de Pós-Graduação em Engenharia de Produção, São Paulo, Brazil.

Frugoli, P. A., Almeida, C. M. V. B., Agostinho F., Giannetti, B. F., Huisingh, D. 2015. Can measures of well-being and progress help societies to achieve sustainable development? Journal of Cleaner Production, 90, 370-380.

Frugoli, P. A., 2012. Estudo Comparativo dos Índices em Emergia e de Indicadores Usuais de Sustentabilidade. Doctorate Dissertation. Universidade Paulista-UNIP, Programa de Pós-Graduação em Engenharia de Produção, São Paulo, Brazil.

Frugoli, A. D., 2013. Análise de Decomposição em Emergia de um Agronegócio: Sustentabilidade e Produtividade Global. Doctorate Dissertation. Universidade Paulista-UNIP, Programa de Pós-Graduação em Engenharia de Produção, São Paulo, Brazil.

Genoni, G. P., Meyer, E. I., Ulrich. A., 2003. Energy flow and elemental concentrations in the Steina River ecosystem (Black Forest, Germany). Aquatic Sciences. 65, 143-157.

Giannetti, B. F., Almeida, C. M. V. B., 2006. Ecologia Industrial: conceitos, ferramentas e aplicações. Edgard Blücher, São Paulo.

Giannetti, B. F., Ogura, Y., Bonilla, S. H., Almeida, C. M. V. B., 2011a. Accounting emergy flows to determine the best production model of a coffee plantation. Energy Policy, 39, 7399-7407.

Giannetti, B. F., Ogura, Y., Bonilla, S. H., Almeida, C. M. V. B., 2011b. Emergy assessment of a coffee farm in Brazilian Cerrado considering in a broad form the environmental services, negative externalities and fair price. Agricultural Systems, 104, 679-688.

Giannetti, B. F., Bonilla, S. H., Almeida, C. M. V. B., 2013a. An emergy-based evaluation of a reverse logistics network for steel recycling. Journal of Cleaner Production, 46, 48-57.

Giannetti, B. F., Demétrio, J. F. C., Bonilla, S. H., Agostinho, F., Almeida, C. M. V. B., 2013b. Emergy Diagnosis and Reflections Towards Brazilian Sustainable Development. Energy Policy, 63, 1002-1012.

Giannetti, B. F., Almeida, C. M. V. B., Agostinho, F., Bonilla, S. H., Ulgiati, S., 2013c. Primary Evidenceson the Robustness of Environmental Accounting from Emergy. Journal of Enviromental Accounting and Management, 1(2), 203-212.

Giannetti, B. F., Agostinho F., Almeida, C. M. V. B., Huisingh, D., 2014. A review of limitations of GDP and alternative indices to monitor human wellbeing and to manage eco-system functionality. Journal of Cleaner Production, 87, 11-25.

Giannetti, B. F., Almeida, C. M. V. B., Agostinho, F., Sevegnani, F., 2016. Advances in Cleaner Production – Volume 2. Nova Publishers

Giorgio, D. V., Friedler, F., Huisingh, D., Klemes, J. J., 2009. Cleaner energy for sustainable future. Journal of Cleaner Production. 17, 889–95.

Goedkoop, M., Spriensma, R., 1999. The Eco-indicator 99: A Damage Oriented Method For Life Cycle Impact Assessment, Methodology Report. Plotterweg, B. V. (Pré-Consultants). 12, 3821 BB Amersfoort, The Netherlands.

Hadley, J., Verberne, W., Wing, L., O'Grady, J., 2002. Corrosion Resistance Without hexavalent Chromium-New Zinc Plating Systems. Metal Finishing. 100, 33-36.

Johnston, C., 1999. An update on zinc plating. Metal Finishing, 97, 40-41.

Lima, C. A. F., 2011. Contabilidade Ambiental em Emergia na Construção do Protótipo Formula UNIP. Master Thesis. Universidade Paulista-UNIP, Programa de Pós-Graduação em Engenharia de Produção, São Paulo, Brazil.

Lupinacci, D. M., 2015. Contabilidade Ambiental de uma Escola de Inglês Localizada no Sul de Minas Gerais-Brasil. Master Thesis. Universidade Paulista-UNIP, Programa de Pós-Graduação em Engenharia de Produção, São Paulo, Brazil.

Mariano, M. V., Almeida, C. M. V. B., Bonilla, S. H., Agostinho F., Giannetti, B. F., 2015. Avaliação em emergia como ferramenta de gestão nos parques urbanos de São Paulo. Gestão & Produção, 22(2).

Mariano, M. V., 2013. Parques Municipais de São Paulo: Contabilidade Ambiental em Emergia. Doctorate Dissertation. Universidade Paulista-UNIP, Programa de Pós-Graduação em Engenharia de Produção, São Paulo, Brazil.

Milaré, E., 1991. Legislação Ambiental do Brasil. Edições APMP, São Paulo.

Nielsen, P. H., Wenzel, H., 2002. Integration of environmental aspects in product development: a stepwise procedure based on quantitative life cycle assessment. Journal of Cleaner Production. 10, 247–257.

Odum, H. T., 1996. Environmental Accounting: Emergy and Environmental Decision Making. Wiley, New York.

Oliveira, J. H., 2015. Contabilidade em Emergia dos Cursos Técnicos em Administração Presencial e EaD do IFSULDEMINAS. Master Thesis. Universidade Paulista-UNIP, Programa de Pós-Graduação em Engenharia de Produção, São Paulo, Brazil.

Roberts, L., 1996. Improving the environmental performance of firms: the experience of two metal working companies. Journal of Cleaner Production. 4, 175-187.

Rossiter, A. P., Kumana, J. D., 1995. Waste minimization through process design. In: Rossiter, A. P. (Ed.), McGraw-Hill, New York.

Sevegnani, F., 2013. Study of Environmental Sustainability of ABC Paulista using Emergy Synthesis. Doctorate Dissertation. Universidade Paulista-UNIP, Programa de Pós-Graduação em Engenharia de Produção, São Paulo, Brazil.

Silva, C. S., Pedrozo, M. F., 2001. Ecotoxicologia do cromo e seus compostos. Série Cadernos de Referência Ambiental. Centro de Recursos Ambientais – CRA (Ed). Vol.5, Salvador, Brazil.

Simões, G. V. A., 2012. Contabilidade Ambiental do Processo de Coleta Seletiva na Cidade de Sorocaba. Master Thesis. Universidade Paulista-UNIP, Programa de Pós-Graduação em Engenharia de Produção, São Paulo, Brazil.

Shonnard, D. R., Hiew. D.S., 2000. Comparative environmental assessments of VOC recovery and recycle design alternatives for gaseous waste stream. Environ Sci Technol. 34, 5222-5228.

Tassinari, C. A., 2013. Avaliação em Emergia da Geração de Hidreletricidade em Usinas Convencionais e Modelo Fio D'água: Estudo de Caso. Doctorate Dissertation. Universidade Paulista-UNIP, Programa de Pós-Graduação em Engenharia de Produção, São Paulo, Brazil.

Telukdarie, A. B., Haung, Y., 2006. A case study on artificial intelligence based cleaner production evaluation system for surface treatment facilities. Journal of Cleaner Production. 14, 1622-1624.

Ukidwe, N. U., Bakshi, B. R., 2004. Thermodynamic accounting of ecosystem contribution to economic sectors with application to 1992 U.S. economy. Environmental Science Technology. 38, 4810-4827.

Vendrametto, L. P., 2011. Contabilidade Ambiental dos Sistemas de Produção Agrícola e dos Serviços do Ecossistema do Cerrado de Lucas do Rio Verde - MT. Doctorate Dissertation. Universidade Paulista-UNIP, Programa de Pós-Graduação em Engenharia de Produção, São Paulo, Brazil.

Zwetsloot, G. I. J. M., 1995. Improving cleaner production by integration into the management of quality, environment and working conditions. Journal of Cleaner Production. 3, 61–6.

5. KNOWLEDGE, INFORMATION AND LIMITATIONS TO AN EFFICIENCY APPROACH TO SUSTAINABLE DEVELOPMENT

Joost Platje

1. Introduction

While knowledge has increased significantly over the last two centuries, it can be argued that potential knowledge has increased even faster (Taleb, 2012). The world has become increasingly complex due to technological advances and increasing trade on a global scale, among other factors. The number, types, and complexity of goods and services produced have increased exponentially since the beginning of the industrial revolution. While knowledge has advanced, the knowledge required to understand the functions of the socio-economic system seems to have increased more rapidly. Before the industrial revolution, most people worked in agriculture, and only a limited number of products were produced. The service sector barely existed, and food processing took place in individual households. Currently, there are millions of products traded each day in large international logistic chains, and the final producer may not have much information about production processes in the earlier phases of the supply chain. While informational problems tend to increase, the impressive progress in science and knowledge is more noticeable than the increasing lack of knowledge and information due to increasing social and economic complexities. Consequently, according to Kahneman (2011) and Taleb (2007, 2012), people may have the illusion of possessing more knowledge than they actually do. This may lead to over-optimism regarding finding solutions for challenges in sustainable development as well as to an increasing reliance on efficiency improvements as a tool. In this chapter, the reasons for increasing complexities, issues regarding efficiency, fragilities, and unsustainabilities, and economic principles used to assess efficiency improvements for sustainable development are discussed.

2. Reasons for Increasing Complexity

The determinants of increasing complexities, and in turn increasing issues in obtaining information and knowledge, can be distinguished. For example, Pejovich (1995) argued that transaction costs (i.e., the frictions in an economy related to information, negotiation, monitoring, and enforcing problems regarding economic transactions) increase in a growing economy. These higher transaction costs not only hamper economic activity but also allow for opportunistic behaviors of individuals and/or groups, such as opportunities created by a lack of transparency and control to increase their own incomes or wealth. When there are several occasions that allow for opportunistic behaviors, people and groups may be provided with strong incentives for redistributive activity and weak incentives for productive activity (Platje, 2004). Transposing this argument to a sustainability discourse, this implies that incentives for lying and cheating become stronger in a case of high transaction costs, which negatively influence environmental protection and the protection of labor rights, for example, and therefore negatively influence sustainable development (Platje, 2011).

In a growing economy, personal exchange is replaced by impersonal exchange. In other words, the market in which people trade with unknown trade partners expands. This increases problems with information and negotiation as well as with the enforcement of transactions or contracts. One example would be a village or small town where all residents are well-known. In this case, people have information about the reliability of their trade partners, as trade takes place repeatedly and the partner is directly identifiable. This makes the trade partner responsible for eventual problems (e.g., bad quality of the good purchased). Incentives for cheating are weak because cheating may lead to a loss of reputation and trade. This reduces negotiation costs (fewer contractual arrangements need to be specified to prevent cheating) and makes it easier to enforce the contract. Although this does not mean there are no problems, these problems are likely to be less complex than in a more extensive market where people do not know each other and a buying or selling transaction may not be repeated with the same person. Trade partners tend to have less information about each other and tend to repeat transactions less often, and thus incentives for cheating become stronger. In such a case, safeguards may be needed to prevent cheating or to compensate for eventual losses (e.g., insurance). This is a type of transaction cost that draws resources away from other productive activity (Williamson, 1985).

An important factor in supporting economic growth is economies of scale, which is caused by capital intensive production. Economies of scale means that when a company produces on a larger scale, the costs of producing one unit decline. In the 1940s, Schumpeter (2003) argued that this is an important source of the creation of wealth in a capitalist system, leading to general access to radios, refrigerators, vacuum cleaners, etc. Even Schumpeter, who was one of few scholars who appreciated the productive and innovative power of the capitalist system at the time he wrote his book (just after the Great Depression of the 1930s when Communism and Fascism were on the rise), did not foresee the incredible progress that would lead to access to inexpensive TVs, computers, mobile phones, photocopying and printing devices, etc. Technological change[5] has created an increasing number and complexity of goods and services. For example, a simple toaster already exists with a wide range of inputs produced by a large chain of producers possessing specific knowledge about the production process, which means that individuals would find it extremely difficult to create a toaster themselves (Harford, 2011).

5 Technology is "the use of scientific knowledge to specify ways of doing things in a reproducible manner" (Brooks, 1971, 13; quoted in Bell, 1976, 29). Thus, it may be interpreted as "society's pool of knowledge" (Mansfield, 1994, 9).

Some decades ago, it would cost tens of thousands of dollars to purchase devices that could only partly provide the services currently provided by a simple computer or smartphone; however, the capital intensification has increased the size of companies, which in turn has increased the costs of management. Companies have become more complex and trade with hundreds or even thousands of other companies in a direct or indirect way. Therefore, this leads to problems in obtaining information and knowledge of all aspects of the production of goods and services, which poses serious challenges to sustainable development.

Once more is produced and more is earned, Pejovich (1995) argued that there would be a struggle regarding the distribution of these gains. This may be a struggle between contract partners or could lead to social conflicts between employers and laborers. Consequently, existing laws, regulations, and contractual arrangements may be questioned, which in turn leads to additional legal cases. It may also lead to increasing dissatisfaction of part of society when the increase in their incomes and wealth does not meet their expectations, for example.

Therefore, there is a question of whether the challenges of sustainability can be managed through efficiency improvements while systems are becoming increasingly complex and interrelated.

3. Efficiency, Fragilities, and Unsustainabilities

Sustainability is interpreted as a situation in which a system can survive, meaning that it can recover from shocks (resilience) and can become stronger and better prepared to manage future challenges through learning processes and different arrangements (e.g., redundancies, buffers). This specifically involves unknown challenges that have a potentially destructive effect on a system. In other words, the system is antifragile (Taleb, 2012) and able to deal with negative Black Swans (Taleb, 2007). Black Swans are uncertain, difficult to imagine, small probability events that can destroy an entire system (e.g., the ecosystem, the financial system, the economic system, the social system, the political system).

For example, the IT revolution was an unexpected event. The Internet was developed by the U.S. army as an instrument in the Cold War against the Soviet Union. It should be difficult to destroy, as it functions as a network with several independent nodes. While it was not meant for general public access, the invention of the modem by Ward Christenen and Randy Suess in 1978 (Castells, 1996) made general access possible; however, in the 1970s, few foresaw the current dependency on IT in all aspects of life. For example, the company Eastman Kodak, which was a leading company in traditional photography equipment and accessories, was negatively affected by the incredible opportunities created by new ways of taking, processing, and printing pictures. It did not adapt properly and almost went out of business.

An example of a negative Black Swan is the Fukushima nuclear plant disaster. Security and risk management models were based on historical data regarding the highest known level of tsunamis caused by earthquakes. The flood protection system could not manage the unexpected tsunami caused by the strongest earthquake on record, which was not predicted by any model. This is the essence of a Black Swan; although something, according to previous knowledge, has never occurred in history, the event could take place. When the potential consequences are disastrous, it is essential to be prepared for such events. For example, the lesson learned from Fukushima is that nuclear plants should not be built in areas prone to strong earthquakes.

A fundamental problem with any type of policy is that information can be limited, incomplete, and missing. Furthermore, people are fallible, their cognitive abilities are limited, and they may be presented with incentives to lie or cheat. These are fundamental reasons for the existence of transaction costs (Furubotn and Richter, 1997).

Transaction costs are fundamental in identifying frictions within a system. Traditionally, analyses focus on friction in conducting business in the market, organizing production within a company (Williamson, 1985), or changing laws or regulations in the political process. Thus, market, managerial, and political transaction costs can be distinguished (Furubotn and Richter, 1997, 43) (see Table 5.1).

Table 5.1 Different types of transaction costs – definitions and some examples

Type of transaction cost	**Transaction costs at the level of governance - market transaction costs**	**Transaction costs at the level of governance - managerial transaction costs**	**Transaction costs at the level of institutional governance - political transaction costs**
Fixed transaction costs	"The costs of setting-up, maintaining or changing an organisational design" (Furubotn and Richter, 1997, 46). Related to the adaptive efficiency of governance structures, i.e., the ability to change when this is required by changing external circumstances, such as technology, competition, and increased scarcity of resources.		"The costs of setting up, maintaining and changing a system's formal and informal political organisation" (Furubotn and Richter, 1997, 47). This is related to creating the legal framework, public administration, military, the educational system, judiciary, etc. (institutional governance and the political system) and costs of institutional change and changing inefficient rulers.
Variable transaction costs	Costs related to frictions in the functioning and use of the market mechanism.	Costs related to frictions in organizing production within the company.	Costs related to frictions in the functioning and use of institutional governance, e.g., the costs of running a polity, stakeholder participation in decision-making, etc. (Furubotn and Richter, 1997).
Information costs (search costs)	Searching for buyers and sellers. Information about culture, reliability, etc. of trade partners. Information on existence, interpretation, and means of enforcement of laws and regulations. What is written in a contract and what is meant by it? Information on the quality of a product or service.	Collecting and processing information for decision-making on, e.g., production plans and technologies.	Information on economic, social and environmental performance. Information on priorities and strengths of different stakeholders. Information on policy alternatives. Information on ownership of property, physical capital, etc. Information on competencies at different administrative levels, etc.
Negotiation costs	Negotiation between and within organizations to establish contractual arrangements. Costs of red tape.	Bargaining between different departments on, e.g., organization of work, production plans, etc. Dealing with internal bureaucracy, paperwork, etc.	Costs of negotiation between different stakeholders on new rules of the game and developing policy.
Control costs (monitoring and enforcement)	Check whether the contract partner fulfils the contractual requirements, e.g., quality of product / service produced, payment, etc. Protection against theft. Costs of obtaining damages for non-fulfilment of the contract (e.g., court, bailiff).	Costs of monitoring the execution of orders and motivating employees.	Costs of implementing and enforcing new rules of the game / policy.

Source: Platje (2011), based on Furubotn and Richter (1997) and Platje (2004).

A transaction can be interpreted as a transfer of rights (Hazeu, 2000, 9) or a contract between two (or more) parties. This notion should be interpreted broadly. A transaction can be formal or informal. It can concern goods, services, and different types of agreements between people as well as the creation and enforcement of laws and regulations. Anything that is based on a type of agreement can be considered a transaction. Transaction costs appear with the design, conclusion, maintenance, protection, and enforcement of a contract. When a good or service is purchased, there are additional costs to the monetary price paid. There are three types of transaction costs: search or information costs, negotiation costs, and control costs. Information and negotiation costs incur before the contract is concluded. This phase is vulnerable to deceit (Molho, 1997) and is related to the aforementioned informational and knowledge problems. After a contract is concluded, the contract partners must eventually be monitored to determine whether they adhered to the agreement. If not, costs related to the enforcement of the contract incur. When the control costs (consisting of monitoring and enforcement costs) are high, this creates opportunities for cheating (Molho, 1997).

In general, the higher the transaction costs, the stronger the incentives to lie and cheat and the weaker the incentives to produce (Platje, 2004, 30). While this does not mean that all people lie or cheat or that people necessarily take advantage of such opportunities, the opportunity costs of honesty appear. This is related to the problem of asymmetric information, meaning that one of the contract partners possesses more information than the other. Suppose someone wants to sell a car. As the seller has been using the car for many years, the seller knows more about its quality than the buyer. Now, imagine that the buyer is not able to determine the quality of the car. Would the seller tell the buyer that there was an accident and the car was repaired three years prior when this would lead to a reduction of $2000 in the selling price? The opportunity costs of being honest would be $2000. The same principle can be applied to issues of sustainable development. For example, what would the consequences be for a meat producer when admitting the meat is produced in an environmentally unfriendly way and that labor rights are neglected? Thus, mechanisms should exist to prevent these situations, such as certificates and transparency in production processes. Furthermore, if the meat producer has a good reputation or brand name, deception regarding the quality or the production process would lead to a loss of the reputation and a loss of customers. In other words, one way to manage the problem is to increase the opportunity costs of cheating.

In addition to deception issues regarding obtaining information and human fallibility, confidence regarding the knowledge possessed as well as the way in which knowledge is obtained must be considered. Knowledge has developed by learning from mistakes (Harford, 2011; Taleb, 2012). In the context of sustainability, the following issues should be considered regarding learning from mistakes and learning by doing:

- Are mistakes reversible, and at what cost? Does damage remain local?
- Do mistakes have non-linear, irreversible effects on a global scale?

For example, if a farmer makes a mistake while crossbreeding potatoes and has a bad harvest, the farmer may go bankrupt (or, in earlier days, starve); however, society can learn from the farmer. If a species dies out due to an overuse of natural resources, people in other areas can learn not to repeat this mistake. As Taleb (2007) argued, the Titanic accident was a tragic mistake that killed several people, but it prevented the development of even larger ships, which could have led to even larger disasters. Thus, reversible mistakes can still result in damage. An individual unit can be injured or die, but the system can become stronger due to the knowledge available as a result. This type of reasoning can be found in evolutionary biology and evolutionary economics.

Now, consider the example of Genetically Modified Organisms (GMOs) (Taleb et al., 2014). While traditional bottom-up genetic engineering took decades to reach a wider area, currently, large bio-technology companies are able to spread GMOs throughout the world in only a few years. Regardless of whether GMOs cause damage or not, if they do cause damage to the ecosystem or to human health, this damage will take place on a global scale. The entire global system would be affected, and the damage may be irreversible and disastrous. It could be argued that the probability of this occurrence is low, but if it did occur, the consequence would be catastrophic. For this type of situation, a precautionary principle should be applied in which more research must be conducted until it is absolutely certain that no harm can be done, as experimenting on a global scale and learning-by-doing processes are too risky. Of course, some economic benefits may be lost, but would the benefits be worth the smallest risk of a global collapse of ecosystems and human health? Taleb (2012) compared this situation to Russian Roulette: society tends to try to obtain small efficiency gains at the expense of an increased risk of system collapse. In this case, the transaction cost of proof of lack of harm should be the responsibility of the producer. If production continues until there is proof of harm, the harm cannot be reversed in a worst-case scenario.

Sustainable development does not refer to a harmonious improvement of all social, economic, and environmental elements because the fundamental assumption of the economic theory is scarcity. Factors of production (physical capital, human capital, natural capital) are limited, while human wants seem to be unlimited, as Adam Smith noted in Wealth of Nations (1998 [1776]). Of course, production possibilities can be increased by expanding the quantity and/or quality of the factors of production; however, using Boulding's (1966) metaphor, as we are living on "The Spaceship Earth," available resources are limited to those available on this planet. Until travel in outer space is possible and efficient, mankind will have to acknowledge these limits. In fact, overpopulation (Hardin, 1968) in combination with the seemingly unlimited appetite for increasing production and consumption are probably the most important causes of the overuse of natural resources. There are currently three general options that can address the problem: a serious reduction in production and consumption, a reduction in the global population, and radical technological advances and efficiency improvements. While the third option should be seriously considered (e.g., see Von Weizszacker et al., 2009), it remains questionable whether mankind can overcome the limits of growth (Meadows et al., 1972).

Suppose a technological breakthrough makes all sun energy available for satisfying human consumption and production demands. The theoretical supply could satisfy an estimated 5000 times the current global demand (King et al., n.d.); however, in addition to the social and economic challenges caused by the decline of industry related to the production and distribution of traditional sources of energy (oil, coal, etc.) as well as challenges in adapting all equipment to the new source of energy, the following challenges would appear (Platje and Kampen, 2016):

- A perceived unlimited supply may lead to increased demand, e.g., due to incentives for innovation. A 10% increase in demand per year would lead to an increase by over 8000% over a period of 90 years.
- Of course, a slower growth of energy use may appear, while new technological developments could make more energy sources available and improve the efficiency of its use; however, with a perceived unlimited availability of energy, incentives to do so may weaken, while incentives to waste may strengthen.
- Innovations due to access to a perceived unlimited amount of inexpensive energy are likely to lead to the use of other limited natural resources, which are currently often already overused. It is unclear whether the resources that would be used most could be predicted, whether all parts of production and processing of the resources' efficiency improvements would be substantial, and whether technological developments would be able to replace all depleting resources.

While it is not impossible that technology could solve all problems, there are several challenges in achieving this due to the existence of millions of goods produced in large international logistic chains with a wide range of producers. These producers must innovate and change production processes. It is unlikely that all would manage at the same time (Platje, 2008). In other words, this is a positive Black Swan: a low probability breakthrough that solves all problems related to environmental sustainability (the social and economic effects are difficult to predict); however, while it may be beneficial to stimulate technological development, particularly experimental research focused on identifying something completely new that can lead to surprising solutions, it may be too risky to completely rely on this approach because when the global ecosystem collapses and natural resources are depleted, the price for the growth and welfare achieved is a collapse of global society and the global economy. For instance, imagine the low-probability scenario that the average global temperature increased by 20 degrees Celsius (Weitzman, 2009). Society as we know it would disappear, and multiple catastrophes are possible from the flooding of countries such as Bangladesh and The Netherlands due to the rising sea level to a large reduction in the output of food. While this is a low-probability scenario, society should question whether it is wise to continue playing Russian Roulette with the environment.

In this context, it should be mentioned again that sustainability and sustainable development is not a harmonious process of a continuous increase in wealth and the quality of life without compromising the opportunities for development for future generations. It involves ecosystem survival (Costanza et al., 1991) and the survival of mankind. Sustainable development should by definition be human-centered regarding the issue of survival. This does not mean that animal and plant life is not important in itself. There is a difference between the aim of survival and the aim of development; killing a grizzly bear out of self-defense as an isolated event may not be harmful, while destroying their habitat for productive aims could lead to the extinction of grizzly bears.

4. Economic Principles Used to Assess the Efficiency Improvements for Sustainable Development

In conclusion, general economic principles that can be used to assess the efficiency improvements for sustainable development are presented. There are several efficiency approaches to issues of sustainable development. Improvements, which range from different types of eco-innovations to improved energy efficiency, can support economic activity while producing goods in a more sustainable way (e.g., Burchard-Dziubińska, 2015; Gądek-Hawlena and Wróbel, 2015; Lambrechts et al., 2015; Piasecka-Głuszak, 2015; Słupik, 2015; Szołtysek, 2015; Will et al., 2015; Zepeda Quintana et al., 2015); however, it is well-known that efficiency improvements can lead to different fragilities in a system and to increased unsustainability via different feedback loops and dynamic effects (Meadows 1998, 1999; Sterman 2000; Taleb 2012).

In textbooks, economics is defined as a science of choice due to the existence of scarcity (Begg et al,. 1994): factors of production (human capital, physical capital, natural capital) are limited, while people tend to prefer more to less. Innovation and efficiency improvements can reduce this problem and can support social and economic developments while preventing negative impacts on environmental resources. Thus, the following fundamental economic principles should be considered when evaluating policies for sustainable development:

1. “Free lunches” do not exist. There are always opportunity costs.

2. When an individual does not incur opportunity costs (i.e., free lunch), these costs are incurred by others. Often, these costs are externalized in a direct or indirect way.

3. While the costs of win-win improvements are not seen, the costs do exist (lack of proof of costs does not mean there are no costs). This is especially the case for long-term, indirect, and uncertain costs. Non-linear costs with very low probabilities that can lead to a non-restorable collapse or crisis are particularly important.

The first principle is the fundamental principle of economic science related to scarcity. Scarcity can be absolute or relative. Absolute scarcity exists in the case of absolute poverty (Todaro, 1997), for example, in which people do not have enough means (food, housing energy, etc.) to guarantee a minimum biological level of existence. Relative scarcity refers to limited resources while people (on average) tend to appreciate an increase in production and consumption. Innovation and efficiency improvements may lead to a reduction in absolute and relative scarcity; however, whether people would continue to obtain more and more is questionable. Furthermore, the issue of fair distribution across the planet must be considered.

The second principle is related to theories of negative externalities, which involve basic environmental economics. People tend to make production and consumption decisions based on their private costs. For driving a car, these costs include gasoline, depreciation, maintenance, and insurance. The external costs appear in the form of pollution, noise, accidents, traffic jams, climate change, etc. Consequently, the social costs (defined as the private cost plus the negative externality) exceed the private costs. Society as a whole experiences the negative effect of a production or consumption decision. For driving a car, people tend to make daily use decisions based on the variable costs of driving.[6] The directly visible cost is the price of gasoline. For this reason, there is the paradox that in a city, it may be more desirable to use a car than public transport from the variable cost perspective. Driving to work may cost $1 for gasoline, while a bus tickets could be purchased for $1.40. If someone were to attend classes 80 miles from home, it would cost $17 for gasoline and $12 for train tickets. While there are additional determinants involved in driving decisions (e.g., opportunity costs of time, preferences for car use), this illustrates a problem in transport policies: while the environmental effects of traffic are the largest in urban areas, using a price policy may have a limited impact.

One issue in environmental management is that when companies comply with environmental standards imposed by the government to address negative externalities, the company can take actions to

6 Fixed costs are costs incurred when the car is not used and is stored in the garage (e.g., insurance, depreciation). Variable costs appear when the owner drives the car (e.g., fuel). Semi-variable costs (or semi-fixed costs) appear at intervals, such as tires and oil having to be replaced each 5000 miles.

shift the cost of this to someone else or to shift the environmental costs to other countries. An example of shifting costs to other parties would be labor and environmental standards in road transport, where the mother company forces the drivers to begin a one-man company with their own trucks. Thus, it forces the drivers to bear the costs of compliance with the rules. The drivers would also bear the risk of a decline in demand for transport services. An example of the second case would be the relocation of pollution activities to countries with more lenient environmental standards.

The third principle needs deeper elaboration because due to the increasing complexity of the market, unexpected costs and issues often appear as a consequence of solutions that appear to be beneficial to everyone (so-called win-win solutions).

The main idea of principle three is that as systems tend to become increasingly complex, an important issue in policy for sustainable development is whether efficiency and innovation support this development or create unexpected and/or unknown threats. Do they make the system more fragile (i.e., hollow out the system, reduce resilience)? For example, an aim of lean management is to improve processes to increase competitiveness and profitability and to reduce resource intensity; however, trade-offs may appear. Changes may cause fear among workers, which could reduce loyalty, decrease the willingness to innovate, and create incentives for finding a new job. Furthermore, introducing additional capital-intensive technologies while laborer's abilities and skills are not developed (making labor easily replaceable, which may be the case with investments in countries due to low labor costs) may lead to footloose capital. "Foot-loose" means that an industry can easily be moved to another country, as it relies on unskilled labor, and that technology and physical capital can be relatively easily transferred to another location. Another example is water access technology. As Meadows (1998) argued, drilling deeper wells does not solve water scarcity. The increased efficiency of drilling methods allows for access to deeper groundwater levels, but it also reduces the groundwater level, creating long-term problems with sustainability and the threat of the collapse of plant life, animal life, and agriculture.

In conclusion, in the economic theory, efficiency seems to be viewed positively. Efficiency refers to accomplishing more with the same resources or to accomplishing the same with fewer resources (e.g., Begg et al., 1994). There is a significant difference between these two definitions regarding sustainable development. The first definition focuses on growth, while the second focuses on maintaining the same level of output while reducing resource use. If the aim is to reduce resource use to the extent that sustainable consumption and production is achieved, the first approach to efficiency would be ineffective. The effectiveness of the second approach depends on the level of the decrease in resource use. A similar argument proposes that more can be done with less: a growing economy can exist while resource use is reduced radically enough to achieve environmental sustainability. It may be that innovation and technological development would not lead to this outcome and that the global system is too complex and interconnected, leading to different types of unsustainable effects. In this case, it may be necessary to do less with less (Shapiro, 1978) and to focus more on the development of local production systems. These systems are less complex and interrelated, which allows for different types of experiments that support transitions to sustainable development (Grin et al., 2010; Leal Filho et al., 2016), and mistakes can lead to learning, knowledge, and improvements, supporting sustainable development.

References

Begg, D., Fischer S., Dornbusch, R. 1994. Economics, fourth edition. London: McGraw-Hill.

Boulding, K.E. 1966. The Economics of the Coming Spaceship Earth. In: Jarrett, H. (ed.). Environmental Quality in a Growing Economy, Essays from the Sixth RFF Forum: 3-14. Baltimore MD: Resources for the Future/Johns Hopkins University Press.

Brooks, H. 1971. Technology and the Ecological Crisis, lecture given at Amherst, May 9, 1971. Quoted in Bell, D. (1976). The Coming of Post-industrial Society: a venture in social forecasting. 29. New York: Basic Books.

Burchard-Dziubińska, M. 2015. Social responsibility, consumption and production patterns in textile and cloth industry in Poland. Economic and Environmental Studies 15(3): 257-270.

Castells, M. 1996. The Rise of the Network Society. Cambridge: Blackwell Publishers.

Constanza, R., Daly, H.E., Bartholomew, J.A. 1991. Goals, Agendas and Policy Recommendations for Ecological Economics. In: Constanza, R. (ed.). Ecological Economics – the science and management of sustainability: 1-20. New York: Columbia University Press.

Furubotn, E.G., Richter, R. 1997. Institutions and Economic Theory - the contributions of the New Institutional Economics. Ann Arbor: The University of Michigan Press.

Gądek-Hawlena, T., Wróbel, M. 2015. The effects of innovative solutions implemented in the supply chain of the public postal operator in Poland. Wrocław School of Banking Research Journal (Zeszyty Naukowe Wyższej Szkoły Bankowej we Wrocławiu) 15(1): 35-44.

Grin, J.; Rotmans, J.; Schot, J., in collaboration with Geels, F. and Loorbach, D. 2010. Transitions to Sustainable Development – new directions in the study of long term transformative change. New York, London: Routledge.

Hardin, G. 1968. The Tragedy of the Commons. Science 62: 1243-48.

Harford, T. 2011. Adapt – why success always starts with failure. London: Abacus.

Hazeu, C.A. 2000. Institutionele Economie – een optiek op organisatie en sturingsvraagstukken. Bussum: Uitgeverij Coutinho.

Kahneman, D. 2011. Thinking, Fast and Slow. London: Penguin Books.

King, D., Browne, J., Layard, R., O'Donnell, G., Rees, M., Stern, N. and Turner, A. (n.d.). A Global Apollo Program to Combat Climate Change, The Global Apollo Program, available at: http://cep.lse.ac.uk/pubs/download/special/Global_Apollo_Programme_Report.pdf, accessed: 15 July 2015.

Lambrechts, W., Van Liederkerke, W., Rymenams, S. 2015. Connecting sustainability initiatives with efficiency measures: an opportunity for business schools. Central and Eastern European Journal of Management and Economics 3(2): 161-173.

Leal Filho, W., Platje, J., Gerstlberger, W., Ciegis, R., Kääriäe, J., Klavins, M. 2016. The Role of Governance in Realising the Transition towards Sustainable Societies. Journal of Cleaner Production 113(1); 755-766. doi:10.1016/j.jclepro.2015.11.060

Mansfield, E. 1994. Applied Macroeconomics. New York: W.W. Norton Company.

Meadows, D.H., Meadows, D.L., Randers, J., Behrens, W. 1972. The Limits to Growth – a report to the Club of Rome. New York: Universe Books.

Meadows, D. 1998. Indicators and Information Systems for Sustainable Development. Hartland: The Sustainability Institute.

Meadows, D. 1999. Leverage Points – places to intervene in a system. Hartland: The Sustainability Institute.

Molho, I. 1997. The Economics of Information – lying and cheating in markets and organizations. Oxford: Blackwell Publishers.

Pejovich, S. 1995. Economic Analysis of Institutions and Systems. Dordrecht: Kluwer Academic Publishers.

Piasecka-Głuszak, A. 2015. The implementation of practical solutions in logistic processes in companies familiar with lean management by means of benchmarking methods. Wrocław School of Banking Research Journal (Zeszyty Naukowe Wyższej Szkoły Bankowej we Wrocławiu) 15(1): 45-47.

Platje, J. 2004. Institutional Change and Poland's Economic Performance since the 1970s – incentives and transaction costs. Wrocław: CL Consulting i Logistyka.

Platje J. (2008). Difficulties with introducing radical eco-innovation in the car industry. Logistyka i Transport 2(7): 69-73.

Platje, J. 2011. Institutional Capital: Creating Capacity and Capabilities for Sustainable Development. Opole: Opole University Press.

Platje, J., Kampen, R. 2016. Climate justice from a club good perspective. International Journal of Climate Change Strategic Management 8(4), in print.

Schumpeter, J.A. (2003 (1943). Capitalism, Socialism and Democracy. Taylor & Francis e-library.

Shapiro, S.J. 1978. Marketing in a Conserver Society. Business Horizon 21: 1-13.

Słupik, S. 2015. Challenges and barriers to sustainable energy consumption in the Silesian Voivodeship. Economic and Environmental Studies 15(3): 303-322.

Smith, A. (1998 (1776)). An Inquiry into the Nature and Causes of the Wealth of Nations. Reprint edited with an introduction by Kathryn Sutherlands (1998). Oxford: Oxford University Press.

Sterman, J.D. 2000. Business Dynamics: system thinking and modelling for a complex world. Boston: Irwin / McGraw Hill.

Szołtysek, J. 2015. The city as a pretext for developing logistic concepts. Wrocław School of Banking Research Journal (Zeszyty Naukowe Wyższej Szkoły Bankowej we Wrocławiu) 15(1): 25-34.

Taleb, N.M. 2007. The Black Swan - the impact of the highly improbable. London: Penguin Books.

Taleb, N.M. 2012. Antifragile - things that gain from disorder. London: Penguin Books.

N.M. Taleb, R. Read, R. Douady, J. Norman, Y. Bar-Yam. 2014. The Precautionary Principle: fragility and black swans from policy actions. Extreme risk initiative – NYU School of Engineering Working Paper Series. Available at: http://arxiv.org/pdf/1410.5787.pdf.

Todaro, M.P. 1997. Economic Development, sixth edition. London: Longman.

Weitzman, M.L. 2009. On modelling and interpreting the economics of catastrophic climate change. Review of Economics and Statistics 91(1): 1-19.

Weizsäcker, E. von, Hargroves, K., Smith, M., Desha, C. and Stasinopoulos, P. 2009. Factor 5: Transforming the Global Economy through 80% Increase in Resource Productivity. London: Earthscan.

Will, M., Haidig, J., Platje, J. 2015. Dysfunctional Leadership – Management in the CSR-case. Central and Eastern European Journal of Management and Economics 3(2): 155-160.

Williamson, O.E. (1985). The Economic Institutions of Capitalism. New York: Free Press.

Zepeda Quintana, D.S., Munguia Vega, N.E., Velazquez, L.E. 2015. The importance of Occupational Safety and Health in Management Systems in the Construction Industry: Case study of Construction in Hermosillo. Central and Eastern European Journal of Management and Economics 3(1): 51-69.

6. ENERGY EFFICIENCY OF GENERAL PURPOSE TECHNOLOGIES – CONTRIBUTIONS TO IMPROVE SUSTAINABILITY

Tino Schuette

1. Introduction

Successful energy management requires plan-do-check-act cycles and continuous improvement procedures overall as well as for specific processes. General purpose technologies (GPT), especially in industrial applications such as illumination, compressed air systems, and electromechanical drives, play very important roles. As can be seen in Table 6.1, which is an example from Germany, the average potential of GPT for increasing energy efficiency is high. The total amount of possible energy savings depends on individual use and the applied technology.

Table 6.1 Average energy efficiency potential of GPT

General Purpose Technology	Potential
Illumination	Up to 70 %
Compressed Air	Up to 50 %
Electromechanical Drives	Up to 30 %
Cooling	Up to 30 %
Heating	Up to 30 %
Ventilation	Up to 30 %
Pumps	Up to 30 %

Source: Dena (2013)

In general, the assessment of the energy performance of a specific GPT should be part of a wider energy analysis. This type of analysis is a detailed investigation of energy supply and use in a company, such as a "maquiladora". The current state of energy performance must be examined and evaluated so that actions can be taken to optimize the system. An energy analysis usually begins with a rough analysis of the overall energy consumption, and areas with a large energy input are determined. The outcomes of this first step are: knowledge of the energy use and energy cost data of crucial consumers, the description of an additional analysis for divisions and processes to be investigated, and evidence of the need for additional energy meters. A detailed analysis must then be conducted to identify the most beneficial opportunities for improving energy performance. Some examples include the course of the energy use of individual devices and subsystems, data on the connection and performance of major appliances (rated power, maximum power, reactive power, etc.), maintenance data (interval, last maintenance, executives, etc.), and knowledge of the key factors that influence energy consumption. During the energy analysis, appropriate energy performance indicators (EPIs) should be expressed that are necessary for suitable benchmarking. An EPI is a (usually specific) quantitative value or measure of energy performance as defined by the company/ organization. According to the DIN EN ISO 50001, benchmarking is the process of collecting, analyzing, and relating the energy performance data of comparable activities to evaluate and compare performances between or within entities. The results of the energy analysis lead to target definitions and the development of an action plan, and actions are assessed and prioritized. The actions are then realized, and the implementation is continuously reviewed.

The necessity of identifying energy saving potential in industrial processes is understood even on a macroeconomic level. In Germany (according to the German Energy Services Act, EDL-G), all companies that are not small or medium-sized enterprises (SME) are obligated to perform an energy audit based on the standard EN 16247-1 until the end of 2015 or to begin the implementation of an energy management system according to ISO 50001 or EMAS (Eco Management and Audit Scheme). SMEs are free to do so as well. In fact, there are several incentives (improving profitability by reducing energy costs or receiving investment subsidies) for companies to analyze and realize energy saving potentials to improve energy efficiency. The following examples of GPT provide insights into improvement possibilities. They are important for several industrial applications, which can also be found in maquiladoras.

2. Illumination

Light is the visible spectrum of electromagnetic waves between about 380 and 780 nm (frequencies of about 789 THz to 384 THz). The characteristics of light are important because they have both physiological and psychological effects on the well-being, performance, and productivity of society. White light is composed of different spectral colors, such as can be seen in a rainbow. Each wavelength has a color impression (from short-wave violet to blue, green, yellow, and orange to long-wave red), and the ranges of color create continuous transitions. The properties of artificial light, such as its ability to reveal the colors of objects faithfully in comparison with natural light (the so-called color rendering index, CRI) or the color temperature, are meaningful. Ideal natural light has a CRI of 100. Good illuminants should have a CRI above 80. The color temperature of light is measured by an ideal black-body radiator that radiates light of a comparable hue to that of the light source. Color temperatures over 5000 K are called cool white (bluish white), while temperatures below 3300 K are warm white (yellowish white through red).

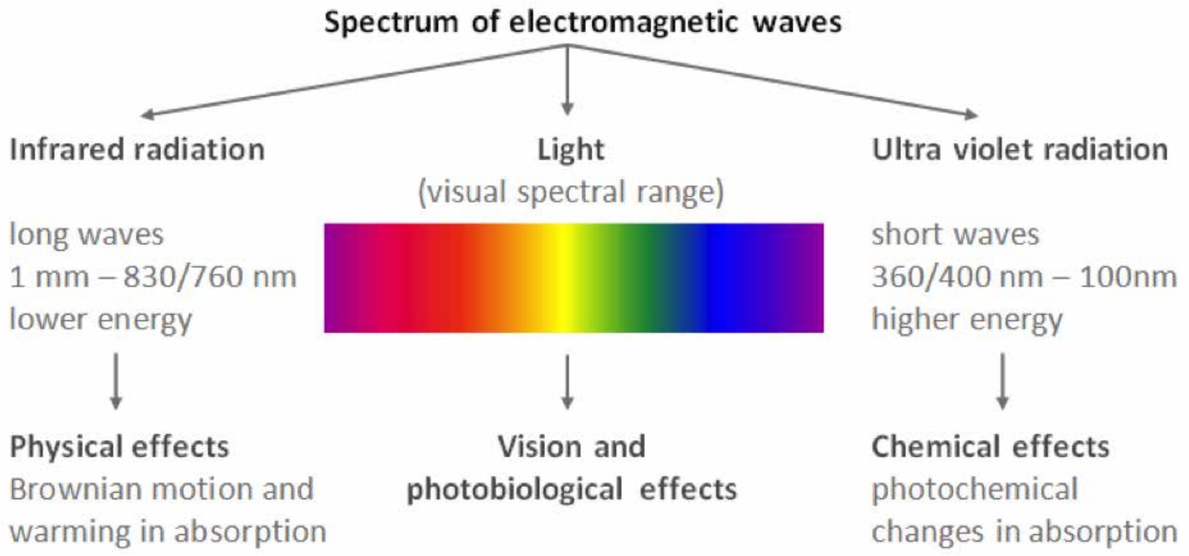


Figure 6.1 Light as Part of Electromagnetic Waves
Source: Author's own elaboration

Important photometric measures of light are the luminous flux [lm], which gives the amount of energy radiated in all directions, the luminous intensity [cd], which gives the luminous flux in one direction, and the illuminance [lx = lm/m^2], which gives the luminous flux on a surface. From an energy focused point of view, the light emitting efficiency [lm/W] is an important measure. Modern spotlights have an emitting efficiency greater than 100 lm/W. In comparison, traditional bulbs only have an efficiency of 10-20 lm/W (Saena, 2013). Important characteristics of spotlights also include their lifespan, luminous flux decline over time, constructive base, light distribution, and optical system. The features of a lamp (size, material, design, etc.) must also be considered. They must be suitable for the lighting task.

There are several major types of spotlights: (i) thermal radiators that generate light by heating a wire in an enclosed gas volume, (ii) luminescence radiators that emit light through electron transitions between different semiconductor layers, and (iii) discharge lamps that emit light through a gas discharge in a firing vessel between two electrodes.

Technical sources of light

Solid state lamps

Thermal radiation
With chemical energy production:
Combustion lamps
With electic energy production:
Vacuum bulbs, gas-filled bulbs (with or without halogen)
Luminescence radiation
e.g. electroluminescence, LED, OLED, laser diode

Discharge lamps

Arc discharge
Open burning
Translucent flasks:
Induction lamps, high-pressure or low-pressure discharge
Glow discharge
With or withou a positive column

Figure 6.2 Types of Light Generation
Source: Author's own elaboration

The advantages of thermal radiators are their good light color and color rendering, a continuous spectrum of light, small dimensions, temperature stability. They are also easily dimmable by an ohmic resistive load. The disadvantages are their low efficiency (<25 lm/W) due to a high proportion of infrared radiation and their short lifetime (<5000 h). The advantages of luminescence radiators are their high efficiency (>100 lm/W, especially as colored light), a long lifespan (>20 000 h), small dimensions, and the possibility of area lights made of organic light emitting diodes (OLED). Their disadvantages are that special control gears (drivers) are required, they are only partially dimmable, their temperature dependence (cooling and moisture protection are important), and the blend risk at high luminous intensities. The general advantages of discharge lamps are their high efficiency (up to >100 lm/W), a long lifespan (>10 000 h), good light color (depending on the gas composition / fluorescent), and color rendering. The disadvantages are that special control gears (current limiter) are necessary, they are only partially dimmable, their temperature dependence (especially regarding their performance and lifespan), and their relatively large dimensions.

To choose the right lamp, the following facts should be considered. Regarding the type of lamp/ construction, whether open or closed lamps and lamps covers are needed should be determined. Moreover, the degree of protection against intrusion, dust, accidental contact, and water by mechanical casings and electrical enclosures (see IEC Standard 60529) and the protection/appliance class (see IEC Standard 61140) needed should be considered. The correct reflector types and light distribution system must be chosen. In addition, the usability in general, such as the mounting and maintenance effort, should be checked. To install an energy efficient illumination system, these basic rules should be followed: 1. prefer the use of natural light, 2. plan in accordance with accepted reference values, 3. select appropriate light characteristics, and 4. conduct a profitability analysis (incl. benchmarking).

Actions can be taken to increase the energy efficiency of existing illumination systems, such as control devices to switch off unused lamps (e.g., by motion detectors or time switches) and adjusting the illuminance to the real requirements. Moreover, spotlights or their components can be exchanged (e.g., bulbs through fluorescent tubes or LED, conventional through electronic ballasts, or big tubes through small ones). Further actions (if necessary) include regular maintenance, reducing the distances between spotlights and the work space, or indirect acts, such as brightening the work environment (e.g., bright walls, floors, and ceilings).

3. Compressed Air

Pneumatic systems are widely used in industrial applications due to their speed, precision, safety, and the relatively low weight of pneumatic tools. Nevertheless, the energy losses are high, as only 25 % of the electrical energy that is needed for compression can be used for the actual work of the pneumatic tool (Dena, 2013). A complete system can be split into the following parts: (i) generation of compressed air, (ii) storage and control devices, (iii) distribution, and (iv) application.

(i) The standard pressure of pneumatic systems for industrial applications is 6.3 bar above atmospheric pressure. A 2-2.5 bar is used for low pressure systems. Applications above 10 bar are called high-pressure systems. The basic components of compressed air generation are the compressor itself and the air treatment, which includes the decrease or elimination of humidity, oil, dust, and pollutants. Both components are usually located close to compressed air energy storage. For the compression of air, different machinery is available, and turbo compressors, piston compressors, and screw compressors are the most popular. Turbo compressors can be distinguished in axial and radial types. They are usually used for high flow rates (> 100 m^3/min) and low pressures (<10 bar). Piston compressors are used for low flow rates (< 20 m^3/min), but high pressures (up to 20 bar) and screw compressors are used for moderate flow rates (<100 m^3/min) and moderate pressures (<16 bar). To choose the right compressor, the level of compressed air needed must be calculated. This also means that opportunities to lower the pressure level (e.g., pressure adjustments, loss reduction) should be considered. Only compressors with a high efficiency should be installed. If the amount of air varies systematically, multiple smaller aggregates should be used rather than one large compressor (that would often run in partial load). The technology used should always be checked for appropriate maintenance.

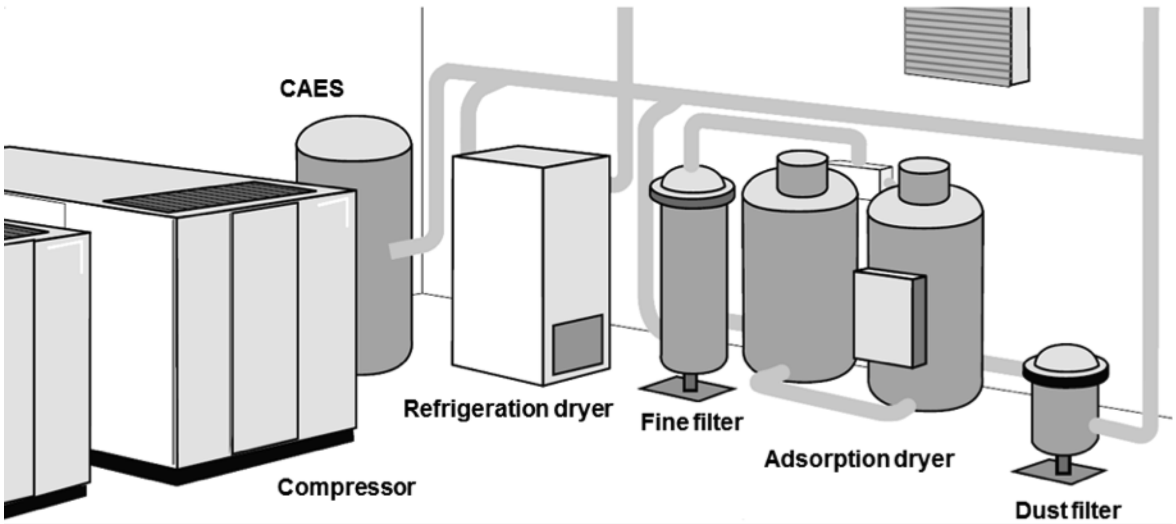


Figure 6.3 Components of a Compressed Air Unit
Source: Atlas Copco (2009)

A condensate separator is necessary for compression and cooling. A condensate is an environmentally hazardous waste and requires suitable disposal. The condensate separator does not replace air drying because the compressed air is still saturated with water vapor. To avoid condensation in the piping systems, fixtures, and appliances, compressed air must be dried either by cold dryers, adsorption dryers, or membrane dryers (for low flow rates). The temperature at which the condensate is released from the air is called the dew point. After the drying filtration of the air, it is necessary to eliminate impurities, such as oils, dusts, and hydrocarbons. The flow through filters creates pressure losses that increase with the grade of filtration (air purity). These pressure losses (as all others) must be compensated for by the compressor's performance. Some measures consider the energy increase with around 10 % needed for 1 bar of additional pressure. Thus, the use of the right filter can save a considerable amount of energy. The same is true for regular filter replacement because the pressure loss increases exponentially when the filter needs to be cleaned or changed.

(ii) The main task of compressed air energy storage (CAES) is the storage and provision of short-term amounts of air at a specific pressure level. CAES can stabilize the required compressor's peak power. Hence, maximum power consumption can be reduced along with the cost of the power supply. In addition to a central system decentralized storage can be used near the air appliances when short-term peak loads occur. When in doubt, a larger CAES should be selected (Dena, 2012). This should also be done when the "pressure content product" (pressure multiplied with volume) requires different inspection intervals, and therefore there are different maintenance costs. A suitable storage system that can make air usage independent from generation should be installed.

The type of (closed-loop) control used for the system has a decisive impact on the energy efficiency of compressed air systems. For instance, with an appropriate superior control, up to 20% of energy costs can be saved (Atlas Copco, 2009). Based on the pressure gradient of the sensors, the control system independently detects the amount of compressed air required. Accordingly, the compressors are switched on or off. It is important that the control unit can determine the performance of the compressors and can independently select the optimal combination. The most common type of control for coordinating multiple compressors is a cascade control in which each compressor is assigned a certain switching range; however, this type of control is only suitable for installations with up to four compressors. For higher-level control systems, a pressure band control with a target pressure setting can be used. Variable speed compressors maintain a preset pressure by varying the air quantity, which eliminates the settings of on or off pressures (Kaeser, 2010).

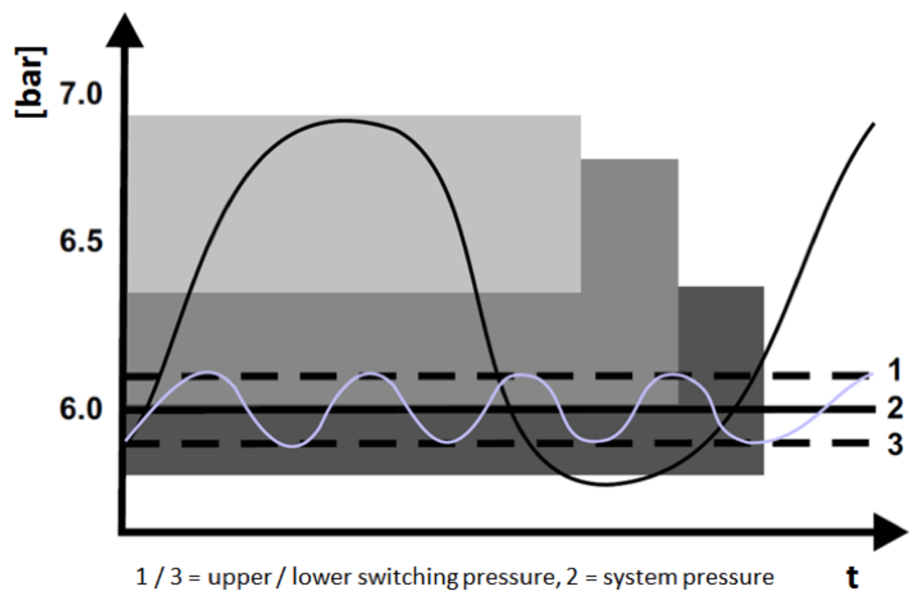


Figure 6.4 Pressure Fluctuations in Cascade Control (dark line) and Pressure Band Control (bright line). The shaded areas symbolize the compressors to be controlled in this stylized superior control scheme.
Source: Author's own elaboration

Internal controls include discontinuous and continuous systems. For compressors, which are not speed-controlled, the full-load-idle-running-control is the most commonly used. When the operating pressure reaches the lower pressure limit, the compressor will start. When the upper pressure limit is reached, the compressor idles. After a predetermined idle time, the compressor is turned off. An advantage of this control scheme is the short reaction time without turning the compressors on and off too often. A disadvantage is that during idling, compressors still consume power. Electrical power consumption during idling can be 20-50% of rated power. Thus, compressors should be speed-controlled if possible (e.g., by frequency conversion). The continuous control system is the most efficient, though the costs for the control system are higher than for discontinuous control systems.

(iii) For the distribution of compressed air, there are main lines, distribution lines, connection lines, and the connections themselves. The main line connects the compressor with the distribution network and should be sized in such a way that reserves are available for future expansion. Distribution lines carry the air to different consumption segments and can be designed as loops or stubs, and there should be a sufficient number of condensate drains with appropriate slopes. Connection lines connect the distribution with the machine workplace. The connection accessories are critical points of a compressed air system. Often, pneumatic fittings and hoses are dimensioned incorrectly and thus lead to unnecessary energy loss. In well-designed compressed air systems, pressure losses should be less than 0.03 bar for each type of line.

If the diameter of the lines is too small, pressure losses increase. The same is true for distribution structures with difficult fixtures (e.g. 90°-curves). Deviation from the correct pressure decreases or increases air consumption and leads to a disproportionate decrease in productivity, or energy waste.

Table 6.2 Relations between flow pressure and air consumption

<table>
<tr><th>Flow pressure at tool [bar]</th><th>Air consumption [%]</th><th>Consequence</th><th>Action</th></tr>
<tr><td>8.0</td><td>125</td><td rowspan="2">wasting of energy</td><td rowspan="2">throttle control</td></tr>
<tr><td>7.0</td><td>111</td></tr>
<tr><td>6.3</td><td>100</td><td>optimal performance</td><td></td></tr>
<tr><td>6.0</td><td>96</td><td rowspan="2">disproportionate decrease in productivity</td><td rowspan="2">pressure increase</td></tr>
<tr><td>5.0</td><td>77</td></tr>
</table>

Source: Dena (2013)

The entire pipe system should be checked for leakage regularly. In old piping systems with no corrosion-resistant materials or defective pneumatic tools, there are often leaks. Based on measurements when no pneumatic tool is working, e.g., by a so-called pumping test, the amount of leakage can be determined. To achieve this, a compressor is started with a fixed flow rate. When the maximum system pressure is reached, the compressor switches to idle. Due to leaks, the pressure in the network drops until the lower switching pressure of the compressor is reached. This process is repeated until a saw-tooth curve arises, which gives access to loading and unloading times. Based on this time series, the amount of leakage can be derived. If it is greater than 10%, leaks in the system should be eliminated. Leakages usually occur in the final meters to the air appliances/consumers (e.g., defective connection hoses, valves, or seals). The leak share can be 20-40% of the produced compressed air quantity (Dena, 2013). Air losses, and therefore energy losses, through leakages are high. For example, a single hole with a diameter of only 1 mm in a 6-bar system causes air losses of 1.2 l/s, which is about 0.3 kW of energy loss. A hole of 3 mm causes losses of 11.1 l/s, or 3.1 kW. Assuming that the system runs 4000 h/a and the price for electricity is 0.1 USD/kWh, the costs would amount to 120 USD/a or 1240 USD/a for just one hole in the line. Leaks in the line network should be eliminated during regular servicing as part of a stringent maintenance strategy.

(iv) The application of compressed air in pneumatic tools, especially at the right pressure, is also important. When the pressure is too high, the generation of compressed air causes unnecessarily high costs. When the pressure is too low, the performance of the tool is reduced, and thus working times are prolonged. A fall below the standard pressure by 10% can result in up to a 50% reduction in performance depending on the tool and application. To reduce pressure losses in connection hoses with flow deflections and small diameters (spiral hoses), their lengths should be as short as possible. Outdated self-venting quick couplings can cause pressure drops of 0.6-1.3 bar (due to a need for a shut-off in the air flow). Modern quick release couplings reduce these losses to 0.2 bar.

Because the potential to improve energy efficiency is often found in the final meters to the tool, the investigation should begin with pneumatic tools (air applications). For a classification of the results of efficiency considerations, it is advisable to compare the energy performance indicators (EPIs) that are available. Benchmarking can take place within a company or between companies. Because many different air application tools result in a variety of pressure levels, pneumatic tools should be grouped. The design of the entire system should then be based on these application groups. Whether there are opportunities to substitute pneumatic tools with electric tools should also be determined.

A pneumatic system should systematically be improved by describing the current state, calculating the target state, evaluating the efficiency potential, and controlling the realized improvements. Another important aspect of a pneumatic system is the (re)use of heat that occurs when compressing air.

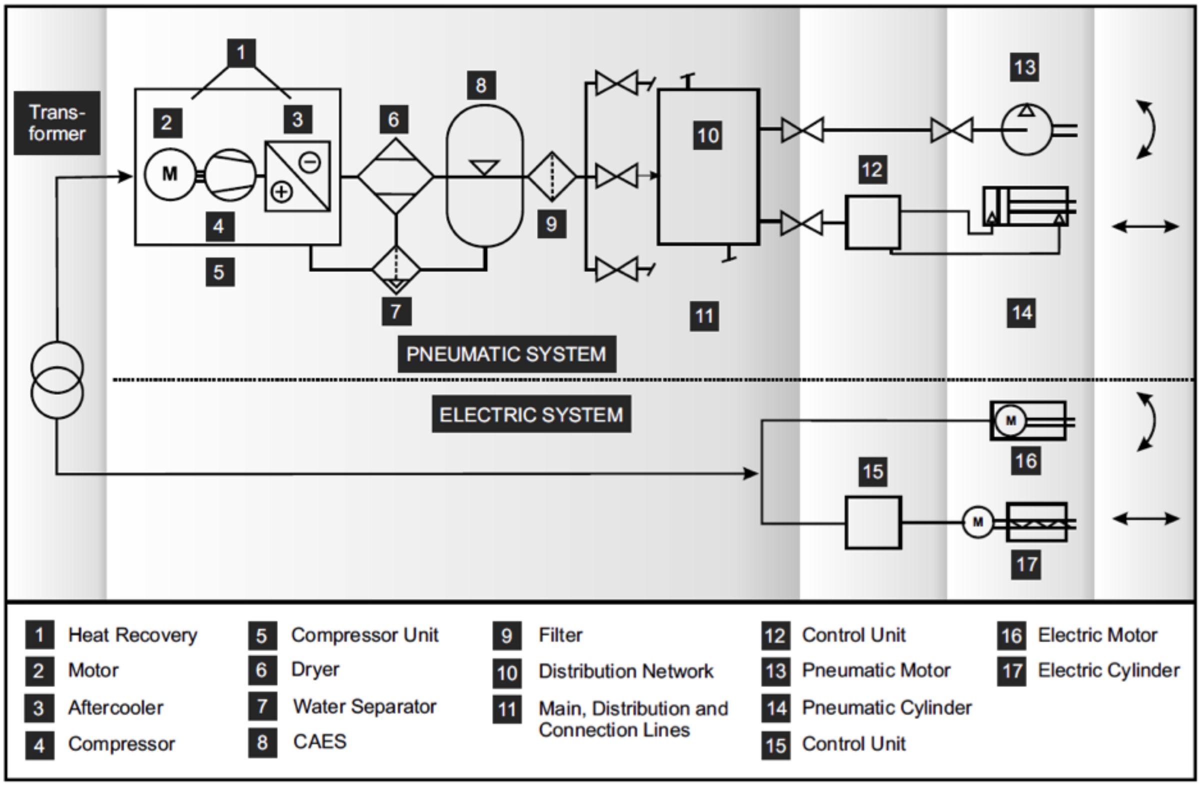


Figure 6.5 Illustration of Energy Conversions
Source: Hesselbach (2012)

4. Electromechanical Drives

Electrical motors and motion devices are crucial in the maquiladora sector because they are necessary not only in pneumatic systems but also for pumps, conveyor technology, or devices for heating, ventilation, and air conditioning. The potential for energy and cost savings is high. In Germany, for example, the possible decrease in the field of drive technology is estimated to be approximately 6 TWh/a (until 2020). Electromechanical drives can be classified as: (i) the electric motor including reactive power compensation, (ii) transmission, (iii) work machines, and (iv) control devices. Work machines are devices used for compressing, pumping, moving, and so on.

When attempting to make energy efficiency improvements to electromechanical drives, the steps used for systematic optimization should be followed: analyzing the current situation, determining the real demand, assessing the energy performance, creating an action plan, implementing the proposed actions, and reviewing the enhanced performance.

(i) Electric motors in general can be divided into AC motors and DC motors. AC motors can be subdivided into synchronous, asynchronous, and universal motors. More than 90% of the motors used in industrial applications are three-phase asynchronous motors. 3~AC motors are virtually free of maintenance due to their robust design. Because the rotor speed is less than the speed of the stator magnetic field, the amount of slip (usually 1-10%) must be considered. In cage induction motors, the rotor windings are short-circuited so that a current is induced to be contactless in the rotor by the alternating field in the stator. This AC motor runs without sparking. In slip-ring induction motors, the rotor windings are led to the outside so that the characteristic of this motor can be changed by resistance in the rotor circuit. This AC motor is therefore suitable for applications with heavy load starts. A disadvantage is that they are more prone to abrasion due to their design. Through the downstream connection of continuously variable transmissions, robust cage induction motors with variable speeds are widely available. Electric motors are mainly standardized by IEC and EN regulations and standards.

The efficiency of asynchronous motors is highly dependent on the energy efficiency and performance class of the motor. For IE3-Motors with 0.75 kW power, for example, the efficiency is approx. 82%, and a motor with 55 kW is approximately 96% (COMMISSION REGULATION (EC) No 640/2009, IE = International Efficiency). Figure 6.6 provides an illustration.

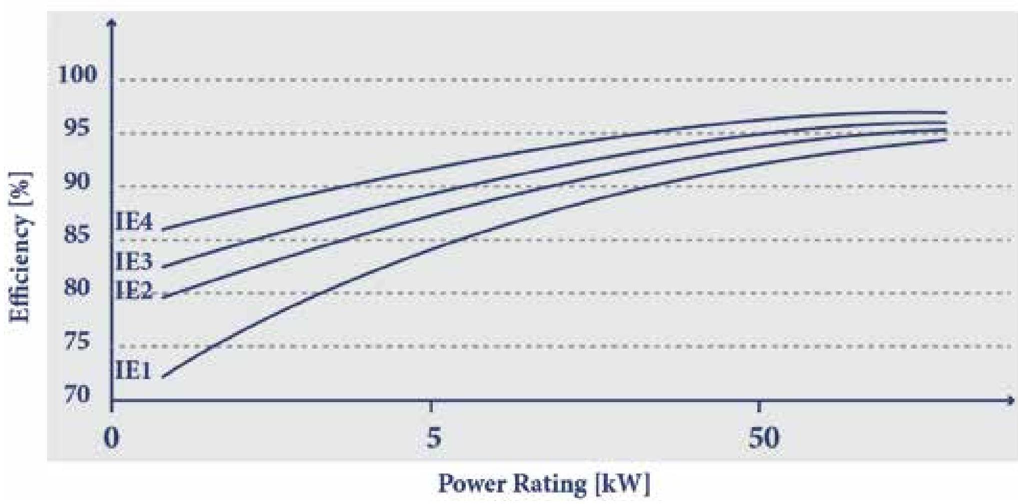


Figure 6.6 Efficiency of Electric Motors
Source: Author's own elaboration

For the selection of electric motors, the operational task, the motor's power consumption, and the operating time, or lifetime, should be considered. Due to their long lifetime, especially for asynchronous motors, the cost for electricity is the primary lifecycle cost. Thus, only electrical motors of a high class of efficiency should be used. Old, inefficient motors should be substituted. For a well-dimensioned system, the electric drive power should not exceed the required power by more than 20%. Common causes of an oversized drive system are missing load profiles or high security surcharges. When there are frequent load fluctuations in the drive, the power consumption can be reduced significantly using frequency converters for speed control. In addition, actions that can reduce reactive power, e.g., by using capacitors, are recommended.

(ii) Transmission units transmit the mechanical power of the electric motor to the work machine. The transmission can be operated directly via a rigid or flexible coupling or indirectly via gears. When indirect connections are used, energy losses of up to 20% are possible (Dena, 2013). Therefore, whether or not direct coupling is possible should always be determined. Variable speeds can also be used through frequency converters in combination with electric motors. When gearboxes with fixed or flexible adjustment mechanisms are used, their efficiency should be checked. Usually, traction drives (such as flat belts, V-belts, toothed belts, or chains) and pinion gears (such as spur gears, bevel gears, worm gears, or planetary gears) are used. Traction drives are usually a cost-saving alternative, but they do have a limited range of transmission ratios. Their nominal efficiency is on average a bit lower compared to pinion gears, which are more expensive but do not require much maintenance. Pinion gears are insensitive to dirt and provide better protection against contact. The various possibilities of gearbox combinations can also improve energy efficiency.

(iii) Some important work machines of electromechanical drives are compressors (see above), pumps, heating, ventilation, including air conditioning applications and material handling. Because they are all GPT groups with several different aspects to consider regarding energy efficiency, they cannot be discussed in more detail in this chapter.

(iv) The control devices of a motor ensure that the engine power is adjusted to the actual need. The most common ways to influence the performance are pole-changing motors, star-delta starting, soft start devices, and frequency converters. For pole-changing motors, the number of revolutions per minute can be changed in stages by changing the number of pole pairs. For a continuous variable speed, control frequency converters are required. Modern converters can return the braking energy of electrical machines to the grid, which can lower the overall power consumption. Using the star operation of an asynchronous motor, the inrush current and the torque are reduced to approximately 30% compared to a delta operation. This is relevant for applications in which the load increases with the speed of the motor, e.g., fans and pumps. For tasks in which the load cannot be connected after start-up, soft starters can be used, which allows for current limiting and torque control.

In sum, illumination systems, compressed air systems, and electromechanical drives are some of the most important GPTs to be taken into account regarding energy consumption due to their wide and intensive use in nearly all industrial companies, from small and medium to large-scale enterprises.

References

Atlas Copco, 2009, Handbuch der Drucklufttechnik, 7. Auflage, Atlas Copco Kompressoren und Drucklufttechnik GmbH.

dena, 2012, Druckluftsysteme in Industrie und Gewerbe, Deutsche Energie-Agentur GmbH (dena).

dena, 2013, Handbuch Energieeffiziente Querschnittstechnologien, Deutsche Energie-Agentur GmbH (dena).

Hesselbach J., 2012, Energie- und klimaeffiziente Produktion, Springer Vieweg.

ISO 50001:2011 (E), Energy management systems - Requirements with guidance for use. International Standard.

Kaeser, 2010, Drucklufttechnik, Kaeser Kompressoren GmbH,

Saena, 2013, Effiziente Beleuchtungssysteme in Produktion, Verwaltung und Handel, Sächsische Energieagentur - SAENA GmbH

7. SERVICE-LEANING FOR SUSTAINABILITY AT THE UNIVERSITY OF VECHTA

Marco Rieckmann

1. Introduction

Currently, humanity is facing a range of global social, economic, cultural, and ecological challenges that threaten the long-term survival of the human species. Therefore, a radical transformation of the economic system, societal organization, and individual lifestyles—a “Great Transformation” *(WBGU – German Advisory Council on Global Change, 2011)*—is needed. Since the Rio Earth Summit in Rio de Janeiro in 1992, the concept of sustainable development has been viewed as a conceptual basis for creating this transformation.

Universities can play a crucial role in facilitating the sustainable development of global society by integrating sustainability as a cross-cutting principle in education, research, campus management, and outreach. Many universities from around the world have already integrated higher education for sustainable development (HESD) in their curricula *(Michelsen 2016; Thomas 2016; Wals et al. 2016)*.

Higher education for sustainable development aims to raise awareness of the unsustainability of the current global development model and to qualify future decision makers to promote the transformation needed. Individuals should be empowered to become change makers *(Heiskanen, Thidell, and Rodhe 2016)*. Therefore, the purpose of higher education for sustainable development is to provide students with sustainability competencies *(Rieckmann, 2012)*. Sustainability competencies are competencies that enable individuals to contribute to sustainable development by promoting societal, economic, and political change as well as transforming their own behaviors. In the academic discourse regarding higher education for sustainable development, several different competencies have been described as crucial for sustainable development. Some of the most important sustainability competencies are systems thinking, futures thinking, values thinking, strategic thinking, collaboration competence, critical thinking, and problem-solving competence *(Gardiner and Rieckmann, 2015; Rieckmann, 2012; Wals, 2015; Wiek et al., 2016)*.

Competencies must be developed rather than taught *(Weinert, 2001)*. Therefore, teaching and learning approaches that are learner-centered and facilitate competence development are needed in higher education *(Barth et al., 2007; Vila, 2012)*. There must be a shift from teaching to learning. Universities should create learning settings that can be characterized by aspects such as self-directed learning, participation, problem-orientation, inter- and transdisciplinary learning, and both formal and informal learning *(Barth et al., 2007)*. These learning settings allow for the development of key competencies needed for managing (un)sustainable development. Thus, particularly suitable pedagogical approaches are project-based learning, research-based learning, and service-learning.

Service-learning engages students in active, relevant, and collaborative learning and is characterized by its equal focus on both the service being provided and the learning that is occurring *(Bringle and Hatcher, 2000).* Bringle and Hatcher (1995, 112) define service-learning as

> "a seminar-based, credit-bearing, educational experience in which students (a) participate in an organized service activity that meets identified community needs and (b) reflect on the service activity in such a way to gain further understanding of seminar content, a broader appreciation of the discipline, and an enhanced sense of civic responsibility."

Sigmon *(1997)* emphasizes the two-way process of learning, which is between those who provide the service and those who receive it, as an experiential education approach that is premised on reciprocal learning. Accordingly, service-learning occurs when there is a balance between learning goals and service outcomes. Engaging students in meaningful projects contributes to deep learning by combining theoretical with practical knowledge and providing them with fundamental concepts. Service-learning programs have an academic context and are designed in such a way that the service aspect enhances learning and the learning process enhances service in an integrated way, rather than as merely a supplementary activity. A significant advantage of service-learning is its combination of formal learning (in the classroom) and informal learning during project work with a partner organization *(Barth et al., 2014).* Both types of learning must be related to one another through reflection. A service-learning project comprises a circle of defining, planning, conducting, and evaluating a project. All steps must be completed by the students in collaboration with their service-partners.

In summary, service-learning enables students to gain new knowledge and develop sustainability competencies in an experiential learning process as active service providers on one hand, and on the other hand, it facilitates organizational changes toward sustainability in the service-partner's institution. The ways service-learning can be implemented in practice are described in the following sections based on the case of the University of Vechta in Germany.

2. Sustainable Development of the University of Vechta

The University of Vechta, which is located in the State of Lower Saxony in Northern Germany, strives to integrate the concept of sustainable development in all functional areas: research and teaching, administration, and campus management. To promote this process, the university established a working group called “Sustainable University” in 2014. The ongoing sustainability activities of the University of Vechta are:[7]

- Student initiatives (e.g., sneep – student network for ethics in economics and practice, and students supporting refugees)
- Campus greening activities (e.g., using recycled paper and Green IT)
- Regional Center of Expertise in Education for Sustainable Development Oldenburger Münsterland
- Research and development projects for sustainable development (e.g., projects on education for sustainable development in teacher education, sustainability-driven entrepreneurship education, and sustainable agriculture)

One of the sustainability research and development projects currently carried out at the University of Vechta is the project “Competencies for A sustainable Socio-Economic development” (CASE).[8] This project is funded by the European Union within the framework of the program “Erasmus Plus – Knowledge Alliances”. The project is implemented by ten partners from five countries under the coordination of the Regional Center of Expertise (RCE), Vienna, located at the Vienna University of Economics and Business. The other partners are Free University Bolzano (Italy), Masaryk University Brno (Czech Republic), University Gothenburg (Sweden), BOKU – University of Natural Resources and Life Sciences (Austria), University of Vechta (Germany), Wiener Stadtwerke (Austria), Terra Institute GMBH (Italy), Environment Center Kapraluv (Czech Republic), and Ekocenter Gothenburg (Sweden). The CASE project aims to support the development of competencies for sustainable socio-economic development. Therefore, the project is developing a curriculum for a joint Master’s program on sustainability-driven entrepreneurship.

For higher education for sustainable development, the University of Vechta offers courses on sustainability in the area of General Studies called “Profilierungsbereich” (profiling area), courses on education for sustainable development in teacher education, and a major in economics and ethics in the Bachelor of Combined Studies. Service-learning is a crucial element of the courses on sustainability in General Studies.

7 See the sustainability website of the University of Vechta (in German): https://www.uni-vechta.de/nachhaltige-hochschule/.

8 http://www.case-ka.eu

3. Service-Learning Courses at the University of Vechta

Since 2014, the University of Vechta has implemented project-based service-learning courses on topics of sustainable development. The courses are offered in the Profilierungsbereich (profiling area) of the Bachelor programs at the University of Vechta. The Profilierungsbereich includes various courses that are offered for different undergraduate study programs (General Studies), which facilitate the development of professional, methodological, social, and action competencies. All undergraduate students at the University of Vechta must take some courses from the Profilierungsbereich. The sustainability modules are part of the section "Developing Action Competencies" of the Profilierungsbereich.

One of the sustainability modules is Module OB-14 Sustainable Development. Table 7.1 displays the service-learning courses that were carried out in this module between 2014 and 2016.

Table 7.1 Courses of the Module OB-14 Sustainable Development

Name of the Course	Sustainable Development in Vechta	Corporate Sustainability Communication
Term	Winter term of 2014/15	Summer term of 2015 / winter term of 2015/16
ECTS	5 CP	5 CP
Students	29	24 / 18
Semesters	3-6	2-6
Program	Bachelor, Profilierungsbereich	Bachelor, Profilierungsbereich
Partners	Local environmental NGO (BUND)	Local enterprises (Lebensbaum; Piepenbrock)

Source: Author's own elaboration

The course "Corporate Sustainability Communication" was offered twice: in the summer term of 2015 in cooperation with the enterprise Lebensbaum, a company that produces organic and partly fair-traded spices, tea, and coffee, and in the winter term of 2015/16 with the enterprise Piepenbrock, a company that offers building cleaning, facility management, maintenance, and security. The course was developed and implemented in the framework of the CASE project as a pilot course in which service-learning in cooperation between the university and local business partners was tested. Both times, the general structure of the course was the same.

At the beginning of the course, the students were informed of their intended learning outcomes:

- To be able to describe the concept of sustainable development
- To be able to reflect critically on the concept of sustainable development and to describe their own points of view
- To be able to explain and compare different relevant strategies and approaches of corporate sustainability communication
- To be able to deal with complex topics and relationships
- To be able to plan, implement, and evaluate a project
- To be able to collaborate with students from different disciplines and relate different disciplinary perspectives

As the course is an optional course for students from different undergraduate study programs, the group is quite diverse. The students are mainly from business and ethics, social sciences, education, social work, and gerontology majors.

To engage students in active, relevant, and collaborative learning, the course is divided into three phases: (1) theoretical input and reflection, (2) project work, and (3) presentation and reflection.

During the six-week theoretical input and reflection phase, special emphasis is given to the clarification of the concepts of sustainability, sustainability communication, and sustainability communication in enterprises in particular. These concepts are presented to the students, and based on inputs and text reading, students must discuss and critically reflect on the concepts. The following teaching and learning methods are used in this phase: short lectures by the teacher, reading academic papers about the different theories and concepts, student group work, and plenary discussions.

During the six-week service-learning oriented project work phase, student groups develop projects for and in cooperation with the service-partners (Lebensbaum and Piepenbrock) supervised by their teacher. The student projects are informed and guided by the theoretical considerations of the input phase. All projects are conceptualized to explore how the sustainability communication of enterprises can be enhanced and improved. This engagement with the "real world" calls for close collaboration between students, teachers, and service partners facilitated by weekly meetings of the project groups and a regular dialogue with the service partners as well as teachers. While some student groups communicate more regularly with the service partners, others have more sporadic contact.

During the two-week presentation and reflection phase, students present the results of their projects to the service partners and the teacher (during an excursion to the enterprise) and reflect on the entire process. The course concludes with written project reports that describe the theoretical background and the project results. The oral presentation, including feedback from the service partners and the teacher, and the report writing within the project group provide the opportunity for critically reflecting on experiences gained during the project work. Table 7.2 illustrates the course schedule.

Table 7.2 Schedule of the "Corporate Sustainability Communication" course

Timeline	**Class titles**
Week 1	Introduction to the course and sustainable development
Week 2	Sustainable economy
Week 3	Sustainability communication I
Week 4	Sustainability communication II
Week 5	Corporate sustainability communication
Week 6	Corporate sustainability communication of a local enterprise
Week 7	Project work
Week 8	Project work
Week 9	Project work
Week 10	Project work
Week 11	Project work
Week 12	Project work
Week 13	Presentation of the results of the projects
Week 14	Final discussion and course evaluation

Source: Author's own elaboration

The course is assessed based on the group presentations of the results of the projects in week 13 and on the submission of the group reports of the project results.

For the project work phase, students are assigned the following task:

- To conduct in groups of 4-5 students a project that focuses on the development of concepts of corporate sustainability communication in cooperation with and as a service for a local enterprise

This task includes the following sub-tasks:

- To choose a challenge of corporate sustainability communication
- To define a target group and communication objectives
- To include concepts from theories
- To develop a communication concept
- If possible, to practically test the communication concept
- To reflect on the results
- To present the results
- To write a report

If needed, each group can receive funding (up to 50 euros), such as for printing posters or flyers.

In week 6, representatives of the local enterprises present their corporate sustainability communication and related challenges to the students. Based on this information, the students choose a challenge to address in their concept development. Some months before the beginning of the course, the enterprises are contacted, and the representatives of the enterprise and the teacher determine which sustainability challenges will be presented to the students.

In the two courses offered in 2015 and 2016, the projects ranged from improving communication of sustainable supply chain management to enhancing social media communication, communicating sustainability in the recruiting process, and developing a concept for sustainability days at the enterprises. Table 7.3 presents four of these projects.

Table 7.3 Four project examples

Project	Sustainable supply chain management	Social media communication	Sustainability in the recruiting process	Sustainability days
Service partner	Lebensbaum	Lebensbaum	Piepenbrock	Piepenbrock
Idea	To visualize how the enterprise selects and controls its suppliers	To use Facebook for communicating the sustainability activities of the enterprise to the customers	To use sustainability in the recruiting process for showing candidates the high sustainability performance of the enterprise	To inform the employees of the enterprise about sustainability and involve them in sustainability activities
Results	A figure that visualizes the sustainability supply chain management that can be included in the sustainability report of the enterprise	A comparison with the Facebook communication of a similar enterprise A concept for enhanced Facebook communication	A concept for making sustainability more visible on the website of the enterprise and in the recruiting process	A concept for sustainability days at the enterprise

Source: Author's own elaboration

All student projects reflect service-learning. Service outcomes were achieved as direct contributions to enhancing the sustainability communication of the enterprises. Furthermore, the courses provided a two-way process of learning involving those who provided a service and those who received it. Thus, a balance between learning processes and service outcomes was achieved.

In the summer term of 2016, the project-based course "Sustainable development in the region Oldenburger Münsterland: Solving problems with innovative projects" was offered in the Module OB-14 Sustainable Development. In this course, which is also a pilot of the CASE project, students investigated the concept of sustainability-driven entrepreneurship and received input from local actors (such as an environmental NGO, a farmers' association, and a common economy group) on regional sustainability challenges. Using this information, student groups developed a business plan for a start-up company that aims to facilitate sustainable development in the region. During this process, students were guided by the teachers as well as by online learning material from the YooWeeDoo-ChangeMaker platform.[9]

9 https://zukunftsmacher-plattform.org/en/

4. Final Thoughts

Because it facilitates the development of sustainability competencies in students, higher education for sustainable development is a key driver for change and transformation. The case of service-learning courses at the University of Vechta shows that service-learning can offer rich learning settings in which students encounter and address real-life sustainability challenges. Based on these activities and the related learning and reflection processes, students can develop various sustainability competencies that are required to manage such challenges. Furthermore, service-learning contributes directly to a sustainable transformation at the local level by supporting local actors in implementing and enhancing sustainability activities. In the case described, the students helped local enterprises better communicate their sustainability activities to the public as well as to their employees.

The implementation of service-learning projects not only requires a high degree of communication and coordination within the student group but also between the students and the service partners. They are equal partners, and for the students, it is a challenge to relate their academic knowledge to the practical knowledge of the service partners. The teachers are responsible for selecting adequate partners for this collaboration, which are partners willing to dedicate at least some time to communication with the students and to provide feedback periodically. Therefore, it is important that the teachers and the service partners clarify their expectations and the conditions of the collaboration before the beginning of the course.

Service-learning is only one approach for creating learning settings in which students can develop sustainability competencies and become change makers. There are other effective teaching and learning approaches, such as research-based learning. All these approaches require a shift from teaching to learning in higher education. Teachers must guide the students and facilitate the process of competence development. Therefore, they must change their roles from teachers to facilitators of the students' learning processes. Achieving this goal by offering service-learning courses on sustainability challenges requires that the teachers themselves have specific competencies, such as sustainability competencies, knowledge about teaching and learning approaches in education for sustainable development, and pedagogical competencies for facilitating these types of teaching and learning approaches (UNECE – United Nations Economic Commission for Europe, 2012). Capacity building and professional development are necessary for teachers to develop these competencies (Barth and Rieckmann, 2012; UE4SD, 2015).

Service-learning, as well as other competence-based teaching and learning approaches, offers several rich learning opportunities for students. At the same time, it enables universities to become involved in local sustainability processes. An increasing number of universities has recognized these opportunities and integrated teaching and learning approaches such as service-learning into their curricula. Both teachers and students can contribute to this transformation process in higher education by demanding change in higher education, directly promoting change, and sharing information. In the framework of the CASE project, different forms of service-learning as well as other innovative teaching and learning approaches are currently piloted at participating universities. In the future, these experiences will be made publicly available at a Knowledge Platform.

References

Barth, M, Adomßent, M, Fischer, D, Richter, S & Rieckmann, M. 2014, 'Learning to change universities from within: a service-learning perspective on promoting sustainable consumption in higher education', Journal of Cleaner Production, vol. 62, pp. 72–81.

Barth, M, Godemann, J, Rieckmann, M & Stoltenberg, U 2007, 'Developing Key Competencies for Sustainable Development in Higher Education', International Journal of Sustainability in Higher Education, vol. 8, no. 4, pp. 416–430.

Barth, M & Rieckmann, M 2012, 'Academic staff development as a catalyst for curriculum change towards education for sustainable development: an output perspective', Journal of Cleaner Production, vol. 26, pp. 28–36.

Bringle, RG & Hatcher, JA 1995, 'A Service-Learning Curriculum for Faculty', Michigan Journal of Community Service Learning, vol. 2, no. 1, pp. 112–122.

Bringle, RG & Hatcher, JA 2000, 'Institutionalization of Service Learning in Higher Education', Journal of Higher Education, vol. 71, pp. 273–290.

Gardiner, S & Rieckmann, M 2015, 'Pedagogies of Preparedness: Use of Reflective Journals in the Operationalisation and Development of Anticipatory Competence', Sustainability, vol. 7, no. 8, pp. 10554–10575.

Heiskanen, E, Thidell, Å & Rodhe, H 2016, 'Educating sustainability change agents: the importance of practical skills and experience', Journal of Cleaner Production, vol. 123, pp. 218–226.

Michelsen, G 2016, 'Policy, politics and polity in higher education for sustainable development' in Routledge Handbook of Higher Education for Sustainable Development, eds M Barth, G Michelsen, I Thomas & M Rieckmann, Routledge, London, pp. 40–55.

Rieckmann, M 2012, 'Future-oriented higher education: Which key competencies should be fostered through university teaching and learning?', Futures, vol. 44, no. 2, pp. 127–135.

Sigmon, RL 1997, Linking Service with Learning in Liberal Arts Education. Available from: http://files.eric.ed.gov/fulltext/ED446685.pdf [29 May 2016].

Thomas, I 2016, 'Challenges for implementation of education for sustainable development in higher education institutions' in Routledge Handbook of Higher Education for Sustainable Development, eds M Barth, G Michelsen, I Thomas & M Rieckmann, Routledge, London, pp. 56–71.

UE4SD 2015, Leading practice publication. Professional development of university educators on Education for Sustainable Development in European countries. Available from: http://www.ue4sd.eu/images/2015/UE4SD-Leading-Practice-PublicationBG.pdf [29 May 2016].

UNECE – United Nations Economic Commission for Europe 2012, Learning for the future. Competences in ESD for educators. Available from: http://www.unece.org/fileadmin/DAM/env/esd/ESD_Publications/Competences_Publication.pdf [29 May 2016].

Vila, LE 2012, 'Higher education and the development of competencies for innovation in the workplace', Management Decision, vol. 50, no. 9, pp. 1634–1648.

Wals, AEJ 2015, Beyond Unreasonable doubt. Education and learning for socio-ecological sustainability in the anthropocene, Wageningen University, Wageningen. Available from: https://arjenwals.files.wordpress.com/2016/02/8412100972_rvb_inauguratie-wals_oratieboekje_v02.pdf [29 May 2016].

Wals, AEJ, Tassone, VC, Hampson, GP & Reams. Jonathan 2016, 'Learning for walking the change: eco-social innovation through sustainability-oriented higher education' in Routledge Handbook of Higher Education for Sustainable Development, eds M Barth, G Michelsen, I Thomas & M Rieckmann, Routledge, London, pp. 25–39.

WBGU – German Advisory Council on Global Change 2011, World in Transition – A Social Contract for Sustainability, WBGU, Berlin. Available from: http://www.wbgu.de/fileadmin/templates/dateien/veroeffentlichungen/hauptgutachten/jg2011/wbgu_jg2011_en.pdf [29 May 2016].

Weinert, FE 2001, 'Concept of Competence: A Conceptual Clarification' in Defining and Selecting Key Competencies, eds DS Rychen & LH Salganik, Hogrefe und Huber, Seattle, Toronto, Bern, Göttingen, pp. 45–65.

Wiek, A, Bernstein, MJ, Foley, RW, Cohen, M, Forrest, N, Kuzdas, C, Kay, B & Withycombe Keeler, L 2016, 'Operationalising competencies in higher education for sustainable development' in Routledge Handbook of Higher Education for Sustainable Development, eds M Barth, G Michelsen, I Thomas & M Rieckmann, Routledge, London, pp. 241–260.

8. A SUSTAINABLE COMPANY IS POSSIBLE - SOME CASE STUDIES AND A MATURITY MODEL

Markus Will

1. Introduction

Businesses of any kind, i.e., not only companies in the public domain or with a vivid public interest, such as utilities, mobility providers, or the banking sector, are expected to take responsibility for social and environmental impacts beyond fulfilling legal requirements. Key stakeholders, such as investors, analysts, and rating agencies, are integrating sustainability factors into their evaluations and investment decisions. Stakeholders such as consumers and non-governmental organizations increasingly require ethically correct behaviors and demand data regarding a company's environmental and social performance. Policy makers, regulators, and standard setters also put pressure on companies. In the European Union, for instance, reporting on sustainability, i.e., non-financial aspects, is now mandatory for larger enterprises with public interests (Directive 2014/95/EU). Companies with more than 500 employees should disclose relevant and useful information regarding environmental matters, social and employee aspects, respect for human rights, anticorruption and bribery issues, and diversity in their board of directors in their reports. Companies are therefore urged to operate in a more socially and environmentally sound way and to manage and improve their sustainability performance. Thus, sustainability has made its way to the boardroom[10]; however, businesses often react to increasing external demands and expectations using rhetoric and means of public relations, i.e., external communication, reporting, and stakeholder participation. This is often more of a camouflage or "blue washing" than true s*ustainability.*

What is true *sustainability*? Sustainability is a regulative concept; it is difficult to explain what sustainability does involve as well as what type of business is sustainable. As with other regulative concepts, such as love, friendship, or justice, it might be helpful to reverse the question. What love does not involve is known. The signs that are definitely not signs of friendship are known. The characteristics of a truly unsustainable company are known. An unsustainable company[11] creates destruction, harm, and damage rather than societal value while maximizing (individual) financial profits. It directly or indirectly contributes to[12]:

- the systematic increase in the exploitation of scarce and non-renewable resources and the increasing quantity of waste from resource extraction

10 EY 2010
11 Schaltegger, 2012:166; Willard, 2009:6.
12 Based on the systems conditions defined by "The Natural Step" (Robert, 2002)

- the systematic increase of the concentration of emissions and hazardous and non-hazardous waste from manufacturing, use, and disposal of products
- the degradation of ecosystem services
- the retention of unsustainable linear take-make-waste production and consumption patterns

The decisions of unsustainable companies are based on inappropriate management systems[13] and information. Sustainability issues are neglected and considered collateral damage. Therefore, decisions might be unsustainable, or improvement projects are insufficient. The business model of an unsustainable company does not reflect sustainability goals and therefore inhibits innovations by promoting and strengthening path dependencies in unsustainable production and consumption patterns, i.e., the take-make-waste pattern and other patterns of unsustainable development. An unsustainable company is clearly a company that practices questionable dealings and markets dubious products (see table 8.1 for examples).

The business model of an authentically sustainable company instead focuses on "doing business, doing good" and the creation of social and environmental value. Actually, it is not related to what a company does with the money earned, such as funding philanthropic activities or donating to charity, but rather how the company makes money (with which resources and under which conditions).

13 Will et al., 2015

Table 8.1 Negative and excluding criteria based on the Common Good Matrix 4.1[14]

Values	Violation of ILO norms (international labor standards) / human rights Products detrimental to human dignity and human rights (e.g., land-mines, nuclear power, GMOs) Outsourcing to or cooperation with companies that violate human dignity
Human dignity	Hostile takeover Blocking patents Dumping Prices
Cooperation and solidarity	Massive environmental pollution Gross violation of environmental standards Planned obsolescence (short lifespan of products)
Ecological sustain-ability	Unequal pay for women and men Job cuts or moving jobs overseas despite having made a profit Subsidiaries in tax havens Equity yield rate > 10 %
Social justice	Non-disclosure of subsidiaries Prohibition of a works council Non-disclosure of payments to lobbyists Excessive income inequality within a business

A sustainable company's practices therefore differ significantly from today's most common business practices. Taken to an idealistic extreme, the sustainable company:

- eliminates unsustainable practices and blacklists unsustainable supplies
- creates value not only for customers but for society as a whole (beyond the creation of jobs and income for employees)
- causes absolutely no direct negative environmental impacts. The company's activities are embedded in social and ecological systems, and they respect their boundaries by using a circular closed-loop production or a cradle-to-cradle approach ("borrow-use-return-model"). Companies conserve non-renewable resources by increasing resource productivity by factors of 5, 10, and 100. Therefore, the company can pursue a growth strategy as long as full decoupling from social and ecological impacts is guaranteed.

14 Based on the initiative "Economy for the Common Good" and according to Felber, 2015

- acts as a “creative destructor” in a Schumpeterian sense, i.e., it provokes a market adjustment by eliminating competitors with sustainability killer applications and products in lead markets
- creates a vision pull, i.e., other companies rigorously attempt to imitate the sustainable business model, thereby transforming economies and initiating breakthroughs with a new paradigm of strong sustainability

Obviously, this radical description of a sustainable business is a type of utopia. Most enterprises will fail to fully meet this ambitious performance level; however, the sketch may guide managers toward a designed transformation process and thus toward sustainability. Before this is discussed in more detail, a proof of concept must be mentioned: sustainable business is possible.

2. Case Studies

There are several examples of successful companies that embrace sustainability and related topics, translate them accordingly to their business models, and align strategic management. These types of sustainable companies typically:

1. Begin by eliminating unsustainable practices
2. Make changes where influence and leverage are high to produce a significant difference
3. Involve suppliers and stakeholders in the product lifecycle
4. Align at the strategic level

In this section, four case studies are presented to illustrate different approaches to and different intensities of sustainability. The case studies were derived from a literature review based on publicly available information and websites.

2.1. Interface[15]

2.1.1. The Sustainability Story

Interface produces and reuses modular carpet tiles. Over time and after more than 50 acquisitions, the company became the world’s largest producer of modular carpets, producing on four continents with sales in more than 100 countries. Interface is a billion-dollar corporation and was named by

15 Based on: http://www.interfaceglobal.com/Sustainability/Interface-Story.aspx (2016-02-23), Andersson and White (2009)

Fortune Magazine as one of the "Most Admired Companies in America" and one of the "100 Best Companies to Work For."[16]

In the early 1990s, the founder and chairman Ray Andersson challenged the entire company to embrace a sustainability vision. This required new thinking and new business models. The development of a new model that overcame the "take-make-waste" approach to manufacturing and distribution was inspired by the international NGO "The Natural Step"[17] and the aligned four system conditions. In the context of a business, this means: using renewable energy, fitting form to function, recycling, and reuse, and creating no waste from operations. To reduce the environmental footprint, Interface has implemented several energy-saving technologies in its factories and uses environmental management and other certification systems, such as LEED[18]. Interface plans to be using 100% renewable energies by 2020. As of 2013, five of seven factories operated with 100% renewable electricity, and 35% of total energy use was from renewable sources. Waste reduction efforts since 1996 have resulted in a 91% decrease in total waste to landfills from production sites[19]. To replace virgin petroleum-based fiber and other raw materials, Interface used 50% recycled or bio-based materials in 2014[20]. As bio-based materials cannot always be considered sustainable[21], the focus is on increasing recycled content in the products (up to 80% or even 100%). Post-industrial recycled materials originate from off-cuts in production processes, while post-consumer materials are collected via a take-back program in cooperation with carpet reclamation companies[22]. The ReEntry Program allows for reclaiming old carpets and feeding them into separating and recycling processes. Each time the tiles need replacement, the customers can choose between cleaning, redesign/reuse, or recycling[23].

2.1.2. What Can Be Learned from This?

Ray Andersson, the former founder and chairman of Interface Inc., which is a multinational producer of carpets, textiles, and architectural products, considered himself a "radical industrialist"[24] and described his journey toward sustainability as being similar to climbing a mountain—a mountain taller that Everest and definitely more difficult to climb. The metaphor of the "mountain" describes not only the size but also the scope of the challenge. Climbing the mountain may be difficult, but it is not impossible. A careful and attentive plan is necessary. Closed-loop business models and products, circular manufacturing, and sourcing processes allow for reducing waste to zero while

16 http://www.interfaceglobal.com/Sustainability/Interface-Story.aspx
17 http://www.thenaturalstep.org/
18 http://www.usgbc.org/leed
19 http://www.interfaceglobal.com/Sustainability/Environmental-Footprint/Waste.aspx (2016-02-23)
20 http://www.interfaceglobal.com/Sustainability/Products/Manufacturing.aspx (2016-02-23)
21 "When is oil greener than corn? 3 obstacles to bio-based materials" Link (2016-02-23)
22 Interface (2013)
23 Interface (2013)
24 Andersson and White (2009)

creating new value for the company (long-term contracts). The sustainable closed-loop business model trickles through the entire supply chain.

2.1.3. What Are the Limits of the Approach?

Currently, only a small percentage of carpets are reclaimed for post-consumer recycling. Interface reclaimed more than 260 million pounds in total, while global carpet removal is estimated at 5 billion pounds annually; however, critics would say that zero waste and overall carpet recycling is still not rigorous enough and that the entire carpet, design, building, and architecture industry must fully embrace sustainability. The selection of recycled or bio-based materials must be based on sound lifecycle assessments to avoid unintended and collateral damage and to ensure lifecycle-wide environmental performance.

2.2. Van Houtum

2.2.1. The Sustainability Story

Van Houtum is a manufacturer and supplier of hygienic paper and solutions for toilet hygiene based in The Netherlands. According to their PR, the company produces the most environmentally friendly toilet paper, Satino Black[25], which is made from 100% recovered paper and is certified according to the C2C silver level standard (see table 8.2). For obvious reasons, used hygienic paper cannot be returned; however, the company encourages consumers to become involved in their recycling concept, such as by returning toilet paper rolls and used office paper to produce hygienic papers on a limited geographical scale to avoid long-distance transport. The ambitions of the company exceed hygienic paper. All chemical substances involved in the production of hygienic paper and soaps have been phased out and replaced by natural and bio-degradable ingredients. Satino Black hygienic paper and soap are therefore suitable for the biological cycle according to the cradle-to-cradle (C2C) principle. Satino Black now has a complementary product line, including soap dispensers[26] and liquid and foam soaps, which are all C2C certified.

25 http://www.vanhoutum.nl/en/brands/5195/satino-black.html (2016-02-23)

26 http://www.c2ccertified.org/products/scorecard/satino_black_dispenser , http://www.c2ccertified.org/products/registry/search&p_company=van_houtum_b.v (2016-02-23)

Table 8.2: Overview on Cradle to Cradle CertifiedTM Product Standard requirements[27]

Material Health	Classification of all chemical ingredients as biological or technical nutrients. Biological nutrients can be safely returned to nature, technical nutrients to industry Determination of potential negative impacts to human health and environment of chemical ingredients, taking into account combination with o
Material Reutilization	Design for recycling Maximization of share of rapidly renewable materials and recycled content Maximization of materials that can be safely reused, recycled or composted at end-of life
Renewable Energy & Carbon Management	Use of renewable electricity and offsetting of carbon emissions at least in final manufacturing stage
Water Stewardship	Managing local geographic and industry water impacts at manufacturing facility Optimization of industrial chemicals in a facilities effluent
Social Fairness	Self-assessments and third party audits in local purchasing and supply chains Making a positive difference in the lives of employees and the local community

2.2.2. What Can Be Learned from This?[28]

Van Houtum is a family run business founded in 1935; however, redesigning the company according to the C2C model naturally fit with the traditional culture of the company. Management realized that innovation based on C2C principles could lead to reshaping the market. Beginning with a pilot, the next step was the integration of suppliers and stakeholders, who were also expected to consider C2C principles and to develop a local-for-local, closed-loop model to retain recovered paper in the region. Van Houtum not only developed a commercial concept based on a dedicated product line, it also organized a campaign for its suppliers to raise awareness and provide training. The company also avoided "green communication"; instead, it focused on design and value for customers.

27 http://epea.com/de/case-studies/van-houtum (2016-02-23), http://www.c2ccertified.org/get-certified/product-certification (2017-02-14)

28 Based on http://www.worldwatch-europe.org/node/181 (2016-02-23)

2.2.3. What Are the Limits of the Approach?

The dispensers are designed to be recyclable; however, only the basic level of the C2C product scorecard is reached. A rigorous return agreement or a leasing model is missing. It is not clear how frequently the materials and inputs can be held in the cycle or if downcycling occurs. In Europe, the regulations for detergents, bio-degradability, and phosphor content are already relatively strict.

2.3. Mud Jeans Leasing Model

2.3.1. The Sustainability Story

Mud Jeans, a Dutch clothes company, was ranked as a more sustainable jeans brand compared to other brands, such as Levi's, Wrangler, or Diesel, by the online platform Rank a Brand[29]. Mud Jeans has implemented measures to reduce the climate impact of production, and it tracks and regularly reports its climate footprint. Raw materials are considered environmentally friendly, i.e., recycled materials and organic cotton are used for almost the entire collection. The company is a member of the Fair Wear Foundation and is involved in improving the conditions of workers in the factories. More recently, the company attracted attention as one of the first to make the circular economy a real-life business model. Mud Jeans offers a temporary ownership; more specifically, it is possible to lease jeans. Customers can pay a monthly fee for wearing the jeans, while Mud Jeans retains ownership of the raw materials, i.e., cotton. Customers are asked to pay a one-time member fee (€ 20, appr. 21 USD)), and they receive their jeans for a monthly fee of € 7.50 (7,43 USD). After twelve months, the customers receive an email offering three options: (1) keep the jeans and stop paying the monthly fee, (2) switch to a new pair and continue with the monthly payment (€ 7,50, app. 7,43 USD), or (3) return the jeans for recycling. In case of returning the jeans, the customer receives a € 10 (approx. 11 USD) voucher to be used later. Mud Jeans also offers a free repair service, up-cycles returned jeans to unique vintage pairs named after the former user, or shreds the jeans. The pieces are combined with virgin cotton to produce new denim yarn while reducing water use by 50%[30].

2.3.2. What Can Be Learned from This?

Due to selling temporary ownership, the company protects itself from volatile cotton prices, while customers are allowed to regularly update their wardrobes without sizeable upfront costs. The company's model shows that a product-service-combination seems to be feasible for products considered to be non-consumables.

2.3.3. What Are the Limits of the Approach?

Sufficiency is not approached at all. The business strategy instead can be considered a clever marketing move that enhances customer retention.

29 http://rankabrand.org/sustainable-denim-jeans/Mud+Jeans (2016-02-23)

30 http://www.mudjeans.eu/lease-a-jeans/ (2017-02-14)

2.4. Ben and Jerry's

2.4.1. The Sustainability Story[31]

Ben and Jerry's, the world-famous ice cream company, has changed its industry sector considerably through creative marketing, endless innovation, and its respectable stance on ethical matters. The company is certified as a Benefit Corporation (B Corp), as it fulfills the highest standards for socially responsible businesses. The company decided to strictly adhere to the following principles:

- Social principles: To operate the company in a way that actively recognizes the central role that business plays in society by initiating innovative ways to improve the quality of life locally, nationally, and internationally
- Product: To make, distribute, and sell the finest quality, all-natural ice cream and euphoric concoctions with a continued commitment to incorporating wholesome, natural ingredients and promoting business practices that respect the Earth and Environment
- Economic: To operate the Company on a sustainable financial basis of profitable growth, increasing value for our stakeholders and expanding opportunities for development and career growth for employees

The principles manifest on different levels and with respect to the different dimensions of sustainability. Ambitious future goals remain negotiable in the case of conflicting goals. For example, long-lasting relationships with local suppliers are considered as more important than a fair trade certification. In line with the social mission statement, fairness with local suppliers and maintaining working relationships is prioritized above certification needs.

Ben and Jerry's declared that it is climate neutral after cutting GHG emissions by 10%, maximizing energy efficiency, and offsetting unavoidable climate impacts by investments in wind farms, biogas, and photovoltaic projects.

2.4.2. What Can Be Learned from This?

An ethical attitude and effective sustainability initiatives work well and can be compatible with business success in conventional terms. Mission statements may help guide the course if translated to real-life projects. Ben and Jerry's is a good example of pursuing established values and using a business model to support a mission statement.

31 This section is based on: http://www.british-assessment.co.uk/articles/ben-and-jerrys-a-model-of-sustainability (2016-02-22)

2.4.3. What Are the Limits of the Approach?

The founder of the company certainly had a mission when starting the business in 1978. Over time, he attempted to make his claim a reality: making the best possible ice cream in the best possible ways; however, the impact of the company is limited because it is a premium market niche within the food industry. It can be assumed that a relatively narrow target group of conscious consumers, called LOHAS[32], are willing to pay higher prices for the products due to the excellent taste and quality of the products. Currently, Benn and Jerry's is a global subsidiary of Unilever[33], which pursues a growth strategy.

3. The Sustainability Journey

The progress of an organization towards sustainability is often described using the metaphor of "a journey." This suggests that a business is moving away from business-as-usual practices by adapting to challenges, aligning strategies, and finally improving performance[34]. Willard applied a five-stage model from pre-compliance (stage 1) to the sustainable company (stages 4 and 5). Companies that are not compliant with legal regulations are considered stage 1 enterprises. Currently, an increasing number of companies are engaged with environmental and social management systems (ISO 14001, ISO 50001, ISO 45000, OHSAS 18001, etc.) and are therefore considered stage 2; however, true sustainability goes beyond legal compliance and an efficiency approach focusing on low-hanging fruits without questioning the raison d'être of the company's activities and outputs. Corporate sustainability management should never begin from scratch. There should be a sound baseline for true sustainability, which is legal compliance. Like a child, a company cannot walk before it can crawl. Therefore, it is rather impossible to skip any stages when trying to make sustainability a part of an organization (see Table 8.3).

32 LOHAS means Lifestyle of Health and Sustainability
33 https://en.wikipedia.org/wiki/Ben_%26_Jerry%27s
34 For a rather critical discussion, see: Milne et al. (2006)

Table 8.3 Overview on Bob Willards' 5-Stage Sustainability Journey[35]

Stage 1: Pre-Compliance	Non-compliance with regulations Prevalent exploitative practices Flouting on environmental, health, and safety regulations Lying and cheating mode of operation, primarily in corrupt jurisdictions without enforcement of standards High exposure to legal and reputational risk if detected
Stage 2: Compliance	Managing liabilities by obeying labor, environmental, health, and safety regulations to avoid fines, prosecution, and bad PR Environmental Management System according to ISO 14001 or EMAS III implemented Effective policies and measures on environmental protection and human rights End-of-pipe pollution abatement technologies installed Reactive approach: fulfillment of legally binding requirements, externalization and off-shoring of environmental and social collateral damages still possible
Stage 3: Beyond compliance	Improved working conditions and active capturing of "low hanging fruits" to enhance eco-efficiency
Stage 4: Integrated Strategy	Rebranding the company as a sustainable one Deep integration of sustainability into business strategies and culture Sustainable borrow-use-return business model (circular economy, cradle-to-cradle) Explicit contribution to the common good, a better world Managerial focus: be a successful company "Stage 4 companies do the right thing because they're good for the company: they're also the right things to do"[36]
Stage 5: Purpose and Mission Driven	All aspects of stage 4 Business strategy and operation reflect purpose and passion Mission-driven business: the goal is to make the world a better place, the mean is a successful company "Stage 5 companies do the right things because they are the right things to do; they're also good for the company" [37]

Companies move voluntarily to stage 3 when they realize that cost reduction is feasible by proactively enhancing energy and resource efficiency. An incremental innovation of internal operations may help to save energy and water and to reduce emissions, waste of production, and packaging.

Sustainability programs are institutionalized (and marginalized) in specialized departments rather than being integrated into the corporate management systems. Measurements clearly focus on

35 Willard, 2009
36 Cited from Willard, 2012:23
37 Cited from Willard, 2012:23

actions that quickly generate results through picking "low hanging fruits" without questioning corporate culture. Stage 3 companies produce the same types of products and services but in a more efficient way. Savings are passed directly to the bottom line (i.e., not reinvested in continuing improvement). Proactive actions are also taken to improve external communication and to avoid negative PR or to discourage new regulations. All this is necessary, as it makes the activities of the company less unsustainable; however, due to the law of diminishing results, the annual goals for reduction of waste generation, electricity consumption, and elimination of toxic substances are increasingly difficult to meet. Companies must therefore take a great leap to transform to stage 4. This requires activities in different stages:

- Stage 3.1:
  - Focus on the supply chain to capture eco-efficiency and improve working conditions of operations and processes of suppliers
  - Greening of the supply chain, i.e., forcing suppliers to fulfill ambitious environmental standards or terminating B2B relations
  - Sustainable procurement
  - Lifecycle assessment of products or Environmental Product Declarations (EPD) to be published
- Stage 3.2:
  - Integration of stakeholders to create innovative and sustainable products and to position the company strategically in new markets (note: this might only be possible for end-product producers)
  - Reinventing product-service-combinations or leases (instead of selling products, combined with obligatory take-back programs)
- Stage 3.3:
  - Integration of sectoral management systems to align a company's governance with sustainability principles
  - Embedded sustainability rules in financial management and investment strategies
  - Comprehensive sustainability reporting and disclosure
  - Internal remuneration and incentive systems focusing on sustainability

The new requirements of ISO 14001:2015 provide beneficial guidelines, particularly with respect to the integration of stakeholders, in consideration of the context of the organization, and from the extended lifecycle perspective, integrating upstream and downstream environmental impacts.

Companies considered sustainability champions, such as Interface, Ben & Jerry's Ice Cream, The Body Shop, or Patagonia, have either undergone an intermediate improvement process (from stage 3 to 4) or have begun their businesses at the end of stage 5. These businesses are typically founder-owned and mirror their founder's values in the organizational culture. They often do not report on or even consider sustainability; rather, they simple implement it.

4. Conclusion

Sustainability is a challenging and complex topic. The normative demands of the concept are contrary to conventional business logic that focuses on profit, growth, and efficiency. When facing a global hyper-crisis (migrations, financial sectors, economic depressions, resource scarcity, environmental problems, etc.), businesses must contribute their shares for the common good. Approaching sustainability with communication tools, such as sustainability reports, often leads to greenwashing, and the enlightened consumer is able to recognize this; however, as shown in this chapter, another business model is possible. There are ways to transform companies from doing business and making profits to contributing to society and the environment. The case studies presented show organizations whose approaches can be used as exemplary models. For a major transformation, efforts of other actors, governments, and customers are necessary. Let's do it. Now.

References

A note on references:

The text in this chapter often reflects personal observations about business sustainability, and it is actually a synthesis derived from several resources, such as academic papers and books, policy documents, reports from consultants and companies as well as discussions on conferences, within businesses, or with students in seminars. In the Age of the Internet, it makes little sense to provide a comprehensive catalogue of each and every source, as most facts can efficiently be checked by a quick web search. It is also sometimes difficult to remember the exact sources of my thoughts, which are the results of years of reflection and observations. Instead, references are only used when directly citing from or referring to a specific piece of work and when providing an overview of specific literature recommended to the reader; however, please adhere to the standards when developing arguments in your own scholarly work.

Andersson, R. and White, R. (2009). Confessions of a Radical Industrialist: Profits, People, Purpose: Doing Business by Respecting the Earth. St. Martin's Press.

EY (2010). The sustainability journey: from compliance, to opportunity, to integration. Insights for North American Committee Members. Ernst & Young Assurance, Tax, Transactions, Advisory. EYGM Limited.

Felber, C. (2015). Change Everything: Creating an Economy for the Common Good, ZED Books 2015.

Interface (2013). ReEntry 2.0 Report.

Milne, M.J., Kearins, K. and Walton, S. (2006): Creating Adventures in Wonderland: The Journey Metaphor and Environmental Sustainability. Organization Vol. 13(6): 801-839. Sage Publishers

Robert, K.H. 2002: The Natural Step Story. New Society Publishers, pg. 242

Schaltegger, S. (2012). Die Beziehung zwischen CSR und Corporate Sustainability. In: Schneider , A. and Schmidpeter, R. (eds). Corporate Social Responsibility. Springer-Verlag, Berlin, Heidelberg.

Will, M., Heidig, J., Platje, J. (2015). Dysfunctional Leadership – Management in the CSR-case. Central and Eastern European Journal of Management and Economics 3(2): 155-160.

Willard, B. 2009. The Sustainability Champion's Guidebook – How to transform your Company. New Society Publishers.

Willard, B. 2012. The New Sustainability Advantage – Seven Business Case Benefits of a Triple Bottom Line. New Society Publishers.

9. LIFE CYCLE ASSESSMENT EXPERIENCES IN MÉXICO: AN AUTOMOBILE EXHAUSTS MANUFACTURING CASE

Javier Esquer, Nora Munguia, David Zepeda

1. Introduction

Increased levels of production and consumption in industrial development remain an obstacle for sustainability (Hueting, 2010) mainly due to the accelerated exploitation of natural resources and environmental pollution (Calvente, 2007), producing irreversible issues that affect human health and quality of life (Matutinovic, 2006). Due to the need to better manage resources and waste to reduce and control environmental impacts as well as to reduce their effects on the population throughout the life cycle of products (Sharma et al., 2010), several tools and methodologies have been used to integrate sustainability principles into production processes (Franceschini and Pansera, 2015).

The Life Cycle Assessment (LCA) technique is one tool used to understand the life cycle environmental performance of products or services (Rebitzer, 2005) and is defined as the compilation and evaluation of the inputs, outputs, and the potential environmental impacts of a product system throughout its life cycle (ISO 14040:2006, 2006). LCA facilitates decision making on issues concerning the environment-industry relationship and allows for reviewing and updating environmental performance indicators along with redesigning products and integrating environmental aspects into products (Sanes, 2012). In this sense, results from this technique are used by managers to make decisions regarding different types of materials, technologies, and energy that have a lower impact on the environment in a holistic, objective, and comprehensive way (Baitz et al., 2004).

The LCA process identifies "hotspots," or inefficiencies, during a product's life cycle (Hortal Ramos, 2006) and has three levels of amplitude (see Figure 9.1). The first is the cradle-to-grave level, which includes all stages of the life cycle (product design, raw material procurement, manufacturing, distribution, use, and disposal), the next level is cradle-to-gate, which includes the initial stage to the finished product at the factory, and, lastly, the gate-to-gate level only considers the manufacturing process (Jacquemin et al., 2012). The LCA may also be applicable to all types of businesses in areas beyond environmental factors, such as cost reduction, loss prevention products, public policies, and corporate images in the market (Lopez, 2008).

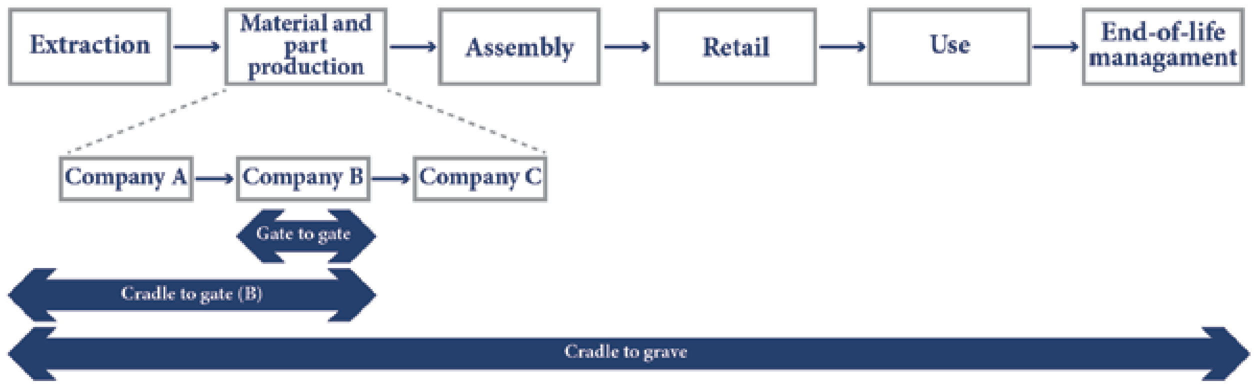


Figure 9.1 Amplitude levels for an LCA
Source: EU/JRC/IES (2010)

Originally, LCA addressed the environmental dimension of sustainability because its goal was to assess environmental impacts without considering social or economic areas involved in the life cycle of a product (Finnveden et al., 2009). Therefore, there is a need for a more comprehensive tool that integrates the three aspects of sustainability (Zhou et al., 2007). It is expected that LCA would promote the optimal use of company resources and avoid unnecessary loss of capital used to enhance sustainable enterprises by quantifying improvements in the processes within the economic, social, and environmental dimensions as well as comparing the current state of the studied system and its possible future states (Klöpffer and Renner, 2008).

Currently, there are variations that complement the environmental impact assessment of traditional LCAs. One of these is the Social Life Cycle Assessment (SLCA), which analyzes the social aspects of workers and consumers during the life cycle of a product (Chang et al., 2015). Another approach is the concept of the life cycle sustainability assessment (LCSA) introduced by UNEP/SETAC Life Cycle Initiative (2011), which is intended to integrate and expand different life cycle assessment techniques: the traditional (Environmental) life cycle assessment (LCA); the life cycle costing (LCC), which is used to assess the cost implications of products' life cycles; and the social life cycle assessment (S-LCA), which examines the social consequences. Furthermore, recently, Keller et al. (2015: pg. 1073) proposed the concept of the integrated life cycle sustainability assessment (ILCSA) to provide "comprehensive ex-ante decision support from a sustainability point of view in the process of establishing new technologies, processes, or products", which is more comprehensive than LCA and LCSA regarding the impacts that can be covered in practice and it can better treat uncertainties connected with the assessment of potential future systems.

In practice, the international standards for LCA, ISO 14040:2006 “Principles and Framework” and ISO 14044:2006 “Requirements and Guidelines,” have been designed to highlight environmental problems and areas for improvement in the production and use of products (ISO 2006). These standards have been complemented by the Institute for Environment and Sustainability in the European Commission Joint Research Center through the International Reference Life Cycle Data System (ILCD) Handbook (EU/JRC/IES 2014) to homogenize the different methodological options and to obtain more accurate results in quality and consistency (Antón Vallejo, 2012).

This chapter aims to present a general overview of an LCA case study conducted in Mexico on automobile exhaust manufacturing as an experience of the Sustainability Graduate Program of the University of Sonora (UNISON).

2. Methodology

The case study described in this document, as shown in Figure 9.2, was conducted using a methodology adapted from the European Platform on Life Cycle Assessment (EPLCA) (EU/JRC/IES 2010), which is also compatible with international LCA standards ISO 14040:2006 (Principles and framework) and ISO 14044:2006 (Requirements and guidelines).

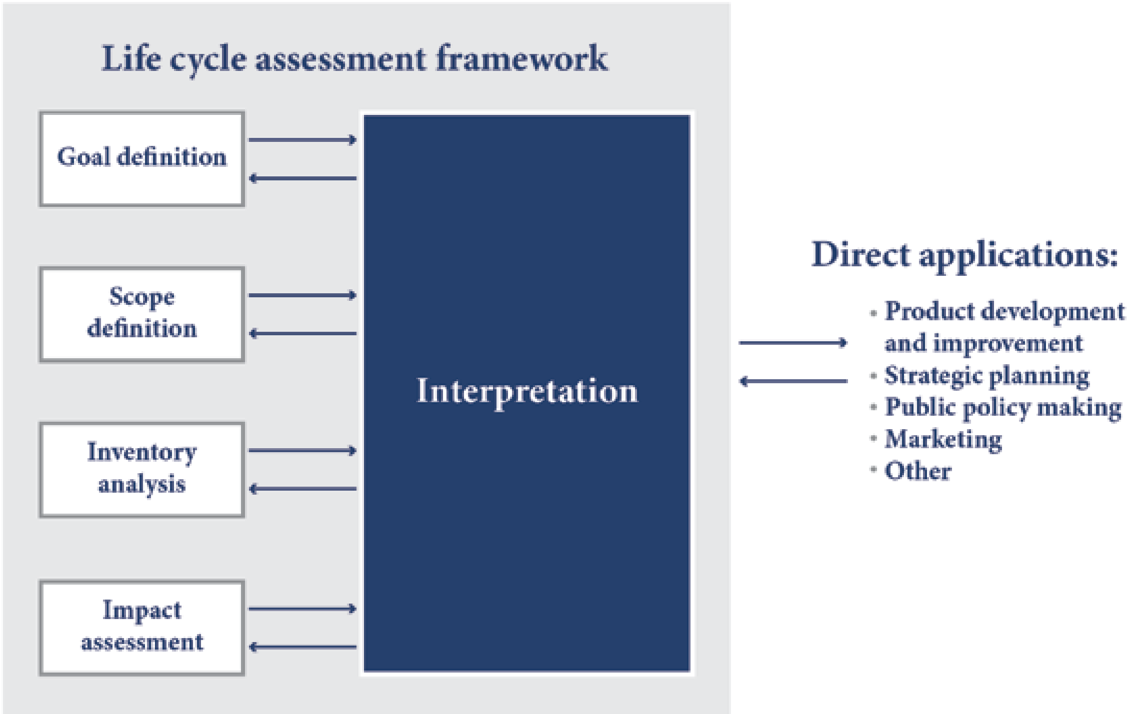


Figure 9.2 Framework for life cycle assessment
Source: EU/JRC/IES (2010)

The reference framework consisted of the following four phases:

1. Defining the objective and scope. To define the object of study and its scope and to determine the limits of the system.

2. Analysis of the Life Cycle Inventory (LCI). In this phase, data from the inputs and outputs under study were collected.

3. Impact Assessment Life Cycle Assessment (LCIA). The information gathered from the ICV was used in this stage to determine the potential impacts on the environment and human health.

4. Interpretation. This was the final phase of the LCA in which the LCI results and the LCIA were discussed and interpreted, conclusions were drawn, and a series of recommendations to reduce environmental impacts were presented.

The study had a cradle-to-gate scope, and it was conducted in an automotive exhaust manufacturing company in the state of Sonora in northwestern Mexico. Data collection included historical data logs and records of the company as well as tools for gathering field information, such as scales, chronometers, and photo cameras. For data processing, the SimaPro® computer program was used to analyze the materials and processes involved in the processes and products.

System boundaries

The system's limits included upstream processes, such as raw material extraction and exhaust hot-end manufacturing. Raw material transportation processes to the plant were excluded, as the company scope is international and thus it has suppliers and customers in several parts of the world, which hinders the monitoring of these processes in an accurate manner. Similarly, infrastructure and consumables were excluded from this study, as they were not part of the objectives.

Functional unit

A ton of finished product was selected as a functional unit, which is the equivalent of approximately 107 hot-end sub-assemblies. A ton was considered the appropriate amount that allowed for a comparison between the input and output of the system.

Methods used for the life cycle analysis impact evaluation

To evaluate the impact of the life cycle, the ReCiPe® method was selected. This combines CML2001® and Eco-Indicator 99® methods, and thus it is an up-to-date method with a high scientific robustness (IHOBE 2009). The main objective of the ReCiPe® was to transform the long list of life cycle inventory results into a limited number of indicator scores that express the relative severity on an environmental impact category (ReCiPe 2016). These indicators were determined at two levels: eighteen midpoint indicators and three endpoint indicators. The midpoint indicators included the following: human toxicity, marine ecotoxicity, metal depletion, climate change, agricultural land occupation, fossil depletion, ionizing radiation, water depletion, terrestrial acidification, photochemical oxidant formation, particulate matter formation, terrestrial ecotoxicity, freshwater ecotoxicity, urban land occupation, freshwater eutrophication, marine eutrophication, natural land transformation, and ozone depletion. The endpoint indicators were: damage to human health, damage to ecosystems, and damage to resource availability.

Inventory analysis

During this phase, all material flows, energy flows, and waste streams released into the environment over the entire life cycle of the system under study were identified and quantified (Zbiciński et al., 2006). The quantifications of both the inputs and outputs of the studied system were mostly analyzed in situ through a guided tour by the company's staff, conducting interviews, and an analysis of production documentation, such as the bill of materials, usually shortened as BOM. Detailed information on the inputs and outputs cannot be published here due to a non-disclosure agreement. The specific case of ceramic composition was based on the percentage values obtained by Lachman et al. (1981). It should be mentioned that ceramics contain precious metals that carry out hydrocarbon and monoxide molecule dissociation, hence producing water and carbon dioxide (Belcastro, 2012); however, the amount of precious metals was not disclosed due to confidentiality reasons.

All processes, materials, and energy from the production stages were identified, and stainless steel was used in virtually all of them. Another resource used in most of the stages was electrical energy for stainless steel transformation, consuming 7,149 kWh per day. Finally, 775.6 L of Argon and 14.5 L of Oxygen were used for welding one hot-end unit. Other materials and resources were scarcely used. Information on raw materials gathered from the system's inputs and outputs was obtained from the Ecoinvent 3® database.

3. Results

Product and production system description

The analyzed product was a sub-assembly called a hot-end that weighed 9.3 kg. It is the first of two parts used in an automotive exhaust. The final product is composed of 90.4% stainless steel, and it is constituted by three main components: a front-end sub-assembly, a cover cone sub-assembly (containing the catalytic converter), and an outlet sub-assembly, as depicted in Figure 9.3. At the end of the production process, the hot-end is wrapped in plastic and placed in a cardboard box that has the capacity to contain 16 sub-assemblies.

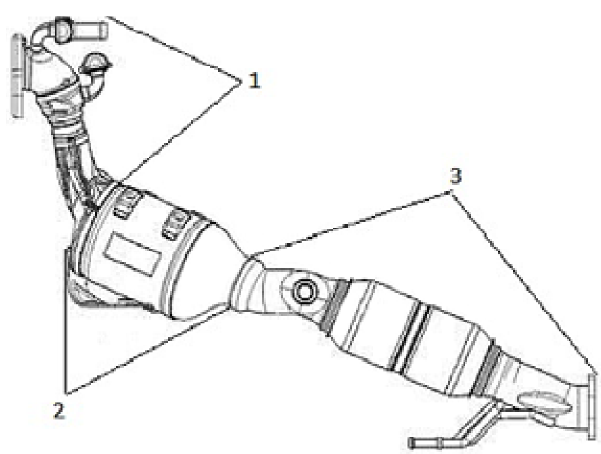


Figure 9.3 Hot-end horizontal plane and its three main components: (1) front-end sub-assembly, (2) convert cone sub-assembly; (3) outlet sub-assembly

The manufacturing process is comprised of nine main stages, as described in Figure 9.4. Three parallel processes are distinguished. The first process includes stages 1 to 4, and it consists of the front-end assembly. It begins with washing the stainless-steel parts in stage 1 to remove pollutants that may hinder its subsequent assembly. During stage 2, 23 welding machines join the parts using pure argon and copper rings. New stainless-steel parts are added in stage 3, which includes manual welding, and in stage 4, in which two welding machines are used. In both stages, an argon/oxygen mixture is used with a 95/5 ratio, respectively.

The second parallel process consists of the outlet sub-assembly, and it includes stages 5 and 6. In stage 5, new pieces of long tubes of stainless steel are incorporated, and then two bending and cutting machines, along with two other machines for the final finish, produce the parts that will be sent and assembled into a flexible tube by four welding machines in stage 6. The final parallel process is stage 7 in which the catalytic converter is added. The latter is a cylindrical-shaped part called a ceramic, which is covered in fiberglass and is protected by a stainless-steel tube that constitutes the convert cone sub-assembly.

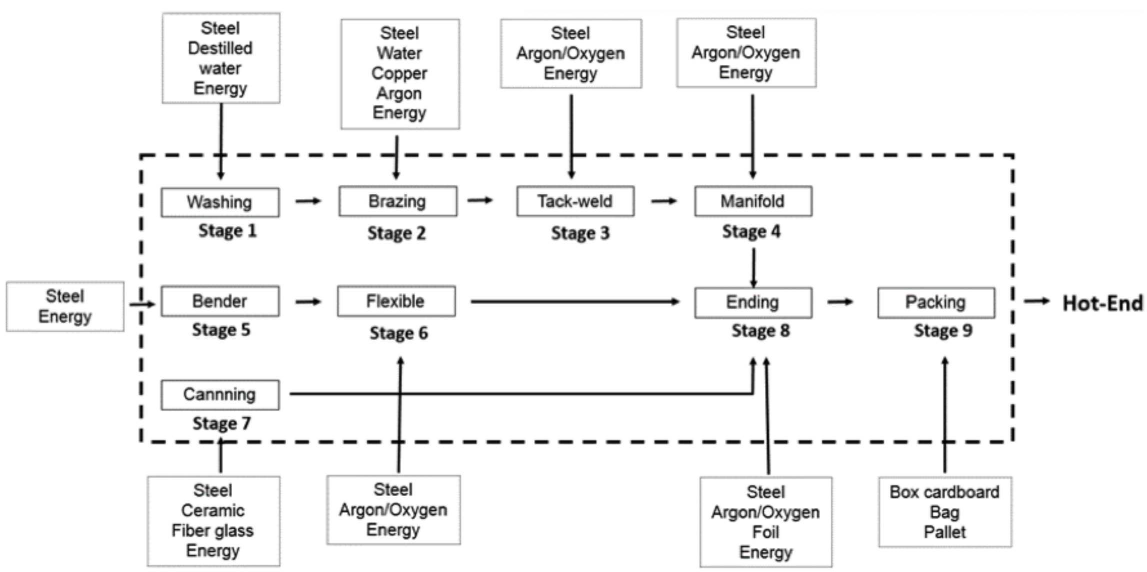


Figure 9.4 Matter and energy input in each of the stages of the hot-end production system

At the end of the three parallel processes, the components reach stage 8 in which they are joined by four welding machines using an argon/oxygen mixture with a 95/5 ratio, respectively. The final product of this stage is the hot-end that is sent to stage 9 for packaging in cardboard boxes.

Characterization and interpretation

The results obtained using the SimaPro® and the ReCiPe® method for the hot-end production process are shown in Table 9.1. All eighteen categories are represented in impact units as well as their total amounts.

The high levels of human toxicity and ecotoxicity are generated by the impact of stainless steel and copper production due to the mining extraction activities and metallurgy process. During the hot-end manufacturing process, copper and stainless steel production have a contribution to human toxicity of 64.9% and 18.8%, respectively. The contribution is similar for marine ecotoxicity: 64.9% is due to copper production, and 26.1% is due to stainless steel. It is worth noting that despite the fact that 19.26 kg of copper and 890.2 kg of stainless steel are used per ton of final product, copper has a higher impact on toxicity due to its production method; however, due to the amount of stainless steel used, this material also has high values in at least six categories: human toxicity, marine ecotoxicity, metal depletion, climate change, agricultural land occupation, and fossil depletion. In comparison, copper has elevated values in the first three of the six categories.

Table 9.1 ReCiPe® midpoint categories resulting from SimpaPro®

Midpoint category	Unit	Total
Human toxicity	kg 1.4-DB eq	13,336.48
Marine ecotoxicity	kg 1.4-DB eq	8,929.11
Metal depletion	kg Fe eq	5,348.56
Climate change	kg CO_2 eq	2,584.61
Agricultural land occupation	m^2a	856.78
Fossil depletion	kg oil eq	827.57
Ionizing radiation	kBq U235 eq	478.84
Water depletion	m^3	118.59
Terrestrial acidification	kg SO_2 eq	19.598
Photochemical oxidant formation	kg NMVOC	10.72
Particulate matter formation	kg PM10 eq	10.41
Terrestrial ecotoxicity	kg 1.4-DB eq	9.41
Freshwater ecotoxicity	kg 1.4-DB eq	2.3
Urban land occupation	m^2a	0.061
Freshwater eutrophication	kg P eq	0.65
Marine eutrophication	kg N eq	0.39
Natural land transformation	m^2	0.046
Ozone depletion	kg CFC^{-11} eq	0.00012

During characterization, the stage with the most significant contribution was stage 2 (brazing) in which 406.6 kg of stainless steel is used per ton of manufactured final product. Furthermore, it is the only stage in which copper and pure argon are used during the welding process. The contributions of each of the stages to the impact categories are shown in Attachment 1.

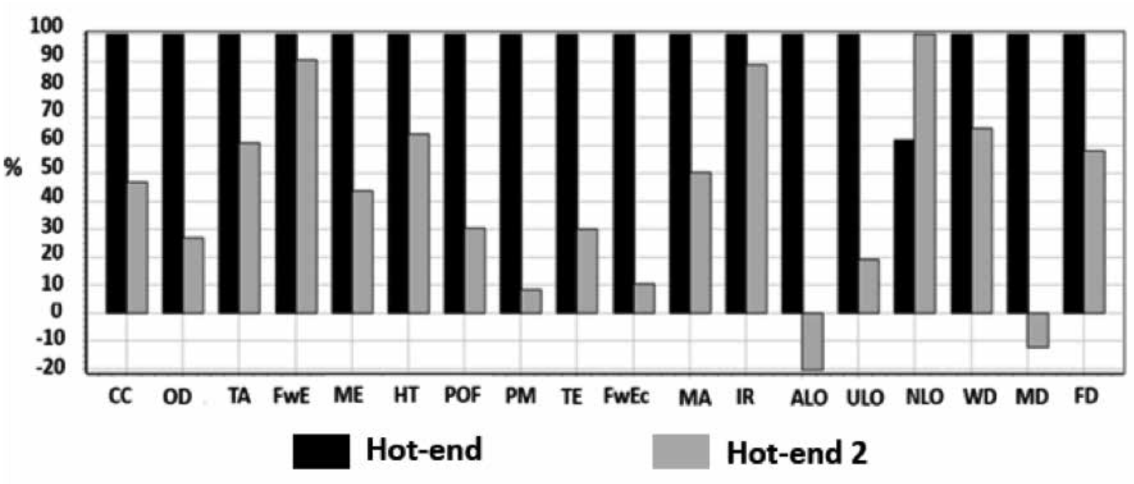
Among the impact categories, metal depletion and climate change also have a significant value. The metal depletion category is greatly affected by the use of stainless steel and copper, contributing 59.5% and 40.5%, respectively. Conversely, argon production has the highest impact on climate change, particularly in stage 2 in which 753.5 kg of argon is required per ton of hot-end, whereas only 31 to 123 kg is used in the other stages.

In addition to the high impacts of stainless steel and copper on human toxicity and marine eco-toxicity categories, both argon and oxygen have considerable impacts on other categories. A cutoff equal to or higher than 5% of impact was performed (see Attachment 2), and it was observed that argon has an impact on sixteen categories. Among the most important are: climate change (1.45E3 kg CO_2 eq), fossil depletion (538 kg oil eq), and ionizing radiation (373 kBq U235 eq). Oxygen has an impact on climate change (271 kg CO_2 eq), water depletion (91.4 m^3), and fossil depletion (63.8 kg oil eq). Other materials, such as cardboard, wood, and distilled water, have low impacts on specific categories. For instance, cardboard and wood affect agricultural land occupation at 204 m^2a and 64.3 m^2a, respectively, whereas distilled water only contributes 6.1 m^3 to the water depletion category.

Sensibility analysis

To perform the sensibility analysis, all stages in which a virgin raw material form of stainless steel was used were considered, and it was substituted with recycled steel as an alternative to reduce impacts. Thus, two models were obtained: a hot-end with virgin raw materials and a hot-end 2 with recycled materials. The results from the characterization are shown in Table 9.2. In most of the ReCiPe® method categories, except natural land transformation, the hot-end 2 had a decreased impact, implying that a positive effect resulted from the implementation of recycled materials, as seen in Figure 9.5.

The categories that exhibited considerable reductions were metal depletion with a reduction of 6.02E+03 kg Fe eq, human toxicity with 4.75E+03 kg 1.4-DB eq, marine toxicity with 4.41E+03 1.4-DB eq, climate change with 1.03E+03 kg CO_2 eq, agriculture land occupation with 1.03E+03 m^2a, and fossil resources depletion with 3.46E+02 kg of oil eq. The decreases in these categories imply a reduction of mining extraction, as the consumption of metals, energy, and chemical substances for extraction and transformation purposes would be reduced, thus also decreasing the areas of exploitation.



CC - Climate change
OD - Ozone depletion
TA - Terrestrial acidification
FwE - Freshwater eutrophication
ME - Marine eutrophication
HT - Human toxicity
POF - Photochemical oxidant formation
PM - Particulate matter formation
TE - Terrestrial ecotoxicity
FwEc - Freshwater ecotoxicity
MA - Marine ecotoxicity
IR - Ionizing radiation
ALO - Agricultural land occupation
ULO - Urban land occupation
NLO - Natural land transformation
WD - Water depletion
MD - Metal depletion
FD - Fossil depletion

Figure 9.5 ReCiPe® category impacts regarding both sub-assembly hot-end and hot-end 2

Table 9.2 Characterization of the ReCiPe® impact categories

Impact Category	Unit	Sub-assembly Hot-end	Sub-assembly Hot-end 2
Climate change	kg CO_2 eq	2,584.61	1,210.89
Ozone depletion	kg CFC-11 eq	0.00012	0.000033
Terrestrial acidification	kg SO_2 eq	19.59	11.95
Freshwater eutrophication	kg P eq	0.65	0.59
Marine eutrophication	kg N eq	0.39	0.17
Human toxicity	kg 1.4-DB eq	13,336.48	8,582.28
Photochemical oxidant formation	kg NMVOC	10.72	3.28
Particulate matter formation	kg PM10 eq	10.39	0.87
Terrestrial ecotoxicity	kg 1.4-DB eq	9.33	2.80
Freshwater ecotoxicity	kg 1.4-DB eq	2.02	0.21
Marine ecotoxicity	kg 1.4-DB eq	8,929.11	4,516.90
Ionizing radiation	kBq U235 eq	139.47	124.35
Agricultural land occupation	m^2a	856.78	-175.09
Urban land occupation	m^2a	25.17	4.85
Natural land transformation	m^2	0.04	0.075
Water depletion	m^3	118.59	78.55
Metal depletion	kg Fe eq	5,348.56	-670.03
Fossil depletion	kg oil eq	827.57	481.39

4. Conclusions

An LCA application in the automotive industry is a highly useful tool for identifying both environmental issues as well as alternatives for material substitutions. The results of this study show that manufacturing an automotive sub-assembly can lead to serious problems for ecosystems, resources, and human health, mainly due to the increase in toxic agents and raw material extraction. This is important because the activities within the plant have low impacts in comparison with the extraction of raw materials for production. The latter can be explained based on the analyzed industry, as product manufacturing consists on a continuous part assembly of previously purchased parts that are joined through energy and other resources, which in turn have a low impact during their utilization in comparison with the energy required and the impacts generated by the extraction and manufacturing of resources.

Thus, the results show that the overall impact of the company is low during hot-end sub-assembly production and that the impact of each manufacturing stage is related to the amount of raw materials used. The resources that cause the highest impacts are of a mining nature: stainless steel and copper; however, the results obtained using the SimaPro® showed that recycled stainless steel may significantly reduce the major environmental impacts previously identified. It is important to note that hot-end sub-assembly is only one of several end products manufactured by this company, and therefore stainless steel is increasingly in demand. An assessment regarding the total amount of steel used for automotive exhaust manufacturing may be useful, as a single automotive exhaust for a medium-sized sedan automobile weighs about 31.4 kg (Ohno et al., 2015) and its composition is constituted by more than 90% of stainless steel.

Finally, the outcomes are relevant considering the automotive industry is one of the largest metal consumers (Ohno et al., 2015). Thus, an understanding of the productive systems of this sector and the creation of environmentally friendly alternatives are key in achieving more sustainable processes and products.

References

Antón Vallejo, M. 2012. Análisis de ciclo de vida aplicado a horticultura protegida. Cuadernos de Estudios Agroalimentarios (CEA), Vol. 3, pp. 211-226. Online 31/X/2016 http://www.publicacionescajamar.es/pdf/publicaciones-periodicas/cuadernos-de-estudios-agroalimentarios-cea/3/3-534.pdf

Baitz, M, Kreißig, J, Byrne, E, Makishi, C, Kupfer, T, Frees, N, Bey, N, Söes Hansen, M, Hansen, A & Bosch, T, Borghi V, Watson, J, Miranda, M. 2004. Life Cycle Assessment of PVC and of principal competing materials. European Commission. Online 15/XI/2016 http://www.pvc.org/upload/documents/PVC-final-report-lca.pdf

Belcastro EL. 2012. Life cycle analysis of a ceramic three-way catalytic converter. Master of Science Thesis. Virginia Polytechnic Institute and State University: Blacksburg, VA.

Calvente, AM. 2007. El concepto moderno de sustentabilidad. UAIS Sustentabilidad. Universidad Abierta Interamericana. Buenos Aires. Argentina. Online 15/XI/2016 http://www.sustentabilidad.uai.edu.ar/pdf/sde/UAIS-SDS-100-002%20-%20Sustentabilidad.pdf

Chang, YJ, Sproesser, G, Neugebauer, S, Wolf, K, Scheumann, R, Pittner, A, Rethmeier, M & Finkbeiner, M. 2015. Environmental and Social Life Cycle Assessment of Welding Technologies. Procedia CIRP, Vol. 26, pp. 293-298.

EU/JRC/IES 2010. International Reference Life Cycle Data System (ILCD) Handbook, First Edition. European Commission Joint Research Centre (JRC)/Institute for Environment and Sustainability. Publications Office of the European Union. Online 08/IV/2016 http://eplca.jrc.ec.europa.eu/

EU/JRC/IES 2014. ILCD Handbook. European Commission Joint Research Centre (JRC)/Institute for Environment and Sustainability. Online 31/X/2016 http://eplca.jrc.ec.europa.eu/?page_id=86

Finnveden, G, Hauschild, MZ, Ekvall, T, Guinée, J, Heijungs, R, Hellweg, S, Koehler, A, Pennington, D & Suh, S. 2009. Recent developments in Life Cycle Assessment. Journal of Environmental Management, Vol. 91, No. 1, pp. 1-21.

Franceschini, S, Pansera, M. 2015. Beyond unsustainable eco-innovation: The role of narratives in the evolution of the lighting sector. Technological Forecasting and Social Change, Vol. 92, pp. 69-83.

Hortal Ramos, M. 2006. La importancia de realizar un análisis de ciclo de vida de forma electrónica. IVACE disseny. Instituto Valenciano de Competitividad Empresarial. Online 30/IX/2013 http://disseny.ivace.es/disseny/index.php?option=com_content&task=view&id=120&itemid=80

Hueting, R. 2010. Why environmental sustainability can most probably not be attained with growing production. Journal of Cleaner Production, Vol. 18, No. 6, pp. 525-530.

IHOBE. 2009. Análisis de ciclo de vida y huella de carbono: Dos maneras de medir el impacto ambiental de un producto. IHOBE, Sociedad Pública de Gestión Ambiental: Bilbao.

ISO 14040:2006. 2006. Environmental management - Life cycle assessment - Requirements and guidelines. International Organization for Standardization. Online 25/X/2016 https://www.iso.org/obp/ui/#iso:std:iso:14044:ed-1:v1:en

ISO. 2006. ISO standards for life cycle assessment to promote sustainable development. International Organization for Standardization. Online 31/X/2016 http://www.iso.org/iso/home/news_index/news_archive/news.htm?refid=Ref1019

Jacquemin, L, Pontalier, PY, Sablayrolles, C. 2012. Life cycle assessment (LCA) applied to the process industry: a review. International Journal of Life Cycle Assessment, Vol. 17, pp. 1028-1041.

Keller, H, Rettenmaier, N, Reinhardt, GA. 2015. Integrated life cycle sustainability assessment – A practical approach applied to biorefineries. Applied Energy, Vol. 154, pp. 1072–1081.

Klöpffer, W, Renner, I. 2008. Life-Cycle Based Sustainability Assessment of Products. In: Schaltegger, S, Bennett, M, Burritt, R, Jasch, C. (eds.), Environmental Management Accounting for Cleaner Production, pp. 91-102. Springer: Netherlands.

Lachman, I, Bagley, R, Lewis, R. 1981. Thermal expansion of extruded cordierite ceramic. Ceramic Bulletin, Vol. 60, No. 2, pp. 202-205.

Löfgren, B, Tillman, AM, Rinde, B. 2011. Manufacturing actor's LCA. Journal of Cleaner Production Journal of Cleaner Production, Vol. 19, pp. 2025-2033.

López, VM. 2008. Sustentabilidad y desarrollo sustentable: origen precisiones conceptuales y metodología operativa. Ed. Trillas, México.

Matutinović, I. 2006. Mass migrations, income inequality and ecosystems health in the second wave of a globalization. Ecological Economics, Vol. 59, No. 2, pp. 199-203.

Ohno, H, Matsubase, K, Nakajima, K, Kondo, Y, Nakamura, S, Nagasaka, T. 2015. Toward the efficient recycling of alloying elements from end of life vehicle steel scrap. Resources, Conservation and Recycling, Vol. 100, pp.11-20.

Rebitzer, G. 2005. Enhancing the application efficiency of life cycle assessment for industrial uses. The International Journal of Life Cycle Assessment, Vol. 10, No. 6, pp. 446.

ReCiPe, 2015. Quick introduction into ReCiPe LCIA Methodology. Online 14/XI/2016 http://www.lcia-recipe.net/project-definition

Sanes, A. 2012. El Análisis de Ciclo de Vida (ACV) en el desarrollo sostenible: Propuesta metodológica para la evaluación de la sostenibilidad de sistemas productivos. Tesis de Maestría. Universidad Nacional de Colombia: Bogotá, Colombia.

Schleicher, U. 1996. The uses of life cycle assessment for European Legislation. The International Journal of Life Cycle Assessment, Vol. 1, No. 1, pp. 42-44.

Sharma, A, Iyer, GR, Mehrotra, A, Krishnan, R. 2010. Sustainability and business-to-business marketing: A framework and implications. Industrial Marketing Management, Vol. 39, No. 2, pp. 330-341.

UNEP/SETAC Life Cycle Initiative. 2011. Towards a Life Cycle Sustainability Assessment: Making informed choices on products. UNEP DTIE: Paris.

Zbiciñski I,Stavenuiter, J, Kozlowska B, van de Coevering, HPM. 2006. Product Design and Life Cycle Assessment. The Baltic University Press: Uppsala.

Zhou, Z, Jiang, H, Qin, L. 2007. Life cycle sustainability assessment of fuels. Fuel, Vol. 86, No. 1–2, pp. 256-63.

Attachment 1. Impact from each production stage

Impact Category	Unit	Washing	Brazing	Tackweld	Manifold	Bender	Flexible	Canning	Ending	Packing	Total
Human toxicity	kg 1,4-DB eq	2,78 E+00	1,20 E+04	1,46 E+02	1,24 E+01	4,83 E+01	2,86 E+02	2,32 E+02	4,56 E+02	1,04 E+02	1,33 E+04
Climate change	kg CO_2 eq	5,29 E-01	1,95 E+03	7,70 E+01	1,11 E+01	1,21 E+01	1,81 E+02	4,22 E+01	2,66 E+02	4,24 E+01	2,58 E+03
Marine ecotoxicity	kg 1,4-DB eq	7,17 E-01	8,11 E+03	1,09 E+02	5,79 E+00	3,26 E+01	1,89 E+02	1,24 E+02	3,20 E+02	3,75 E+01	8,93 E+03
Fossil depletion	kg oil eq	1,73 E-01	6,49 E+02	2,03 E+01	3,03 E+00	3,32 E+00	5,14 E+01	1,14 E+01	7,49 E+01	1,42 E+01	8,28 E+02
Water depletion	m^3	1,58 E+00	3,06 E+01	1,32 E+01	2,66 E+00	2,67 E-01	2,87 E+01	9,21 E-01	3,98 E+01	8,38 E-01	1,19 E+02
Metal depletion	kg Fe eq	8,70 E-04	4,56 E+03	1,21 E+02	1,60 E+00	3,80 E+01	1,72 E+02	1,32 E+02	3,20 E+02	1,34 E-01	5,35 E+03
Ionizing radiation	kBq U235 eq	6,42 E-02	1,08 E+02	3,64 E+00	7,33 E-01	5,18 E-01	1,02 E+01	1,12 E+00	1,41 E+01	1,47 E+00	1,39 E+02
Agricultural land occupation	m^2a	1,01 E-03	4,48 E+02	2,13 E+01	4,17 E-01	6,53 E+00	3,15 E+01	2,33 E+01	5,76 E+01	2,69 E+02	8,57 E+02
Terrestrial acidification	kg SO_2 eq	4,43 E-03	1,54 E+01	5,01 E-01	7,78 E-02	7,74 E-02	1,19 E+00	2,85 E-01	1,73 E+00	3,29 E-01	1,96 E+01
Urban land occupation	m^2a	1,32 E-03	1,87 E+01	7,35 E-01	7,63 E-02	1,37 E-01	1,47 E+00	4,94 E-01	2,29 E+00	1,29 E+00	2,52 E+01
Photochemical oxidant formation	kg NMVOC	1,60 E-03	8,18 E+00	3,09 E-01	3,69 E-02	5,75 E-02	6,77 E-01	2,17 E-01	1,03 E+00	2,19 E-01	1,07 E+01
Particulate matter formation	kg PM10 eq	1,24 E-03	7,91 E+00	3,30 E-01	3,28 E-02	6,84 E-02	6,56 E-01	2,42 E-01	1,03 E+00	1,29 E-01	1,04 E+01
Terrestrial ecotoxicity	kg 1,4-DB eq	4,76 E-05	8,32 E+00	1,43 E-01	4,41 E-03	4,15 E-02	2,30 E-01	1,52 E-01	4,07 E-01	4,13 E-02	9,34 E+00
Freshwater ecotoxicity	kg 1,4-DB eq	1,21 E-03	1,62 E+00	4,78 E-02	3,06 E-03	1,95 E-02	8,84 E-02	6,55 E-02	1,46 E-01	4,16 E-02	2,03 E+00
Marine eutrophication	kg N eq	5,10 E-05	2,95 E-01	1,00 E-02	1,28 E-03	1,72 E-03	2,23 E-02	6,74 E-03	3,36 E-02	2,00 E-02	3,91 E-01
Freshwater eutrophication	kg P eq	3,35 E-05	6,16 E-01	4,30 E-03	6,88 E-04	6,02 E-04	1,05 E-02	1,77 E-03	1,52 E-02	6,05 E-03	6,56 E-01
Natural land transformation	m^2	4,51 E-06	3,61 E-02	1,18 E-03	3,71 E-04	-1,51 E-04	3,91 E-03	-8,66 E-04	4,92 E-03	1,52 E-03	4,70 E-02
Ozone depletion	kg CFC-11 eq	2,13 E-08	9,61 E-05	3,43 E-06	3,76 E-07	7,13 E-07	7,53 E-06	2,74 E-06	1,16 E-05	2,37 E-06	1,25 E-04

Attachment 2. Impacts from main materials (≥5%)

Impact category	**Unit**	**chrome**	**copper**	**argon**	**oxygen**
Human toxicity	kg 1,4-DB eq	2.51E3	8.66E3	1.44E3	
Marine ecotoxicity	kg 1,4-DB eq	2.3E3	5.68E3	698	
Metal depletion	kg Fe eq	3.1E3	2.17E3		
Climate change	kg CO_2 eq	726		1.45E3	271
Agricultural land occupation	m^2a	545			
Fossil depletion	kg oil eq	183		538	63.8
Ionizing radiation	kBq U235 eq			373	59.4
Water depletion	m^3	21.1		12.6	91.4
Terrestrial acidification	kg SO_2 eq	4.04	4.05	8.93	1.99
Photochemical oxidant formation	kg NMVOC	3.93	0.63	4.99	0.86
Particulate matter formation	kg PM10 eq	5.03	0.95	3.44	0.81
Terrestrial ecotoxicity	kg 1,4-DB eq	3.45	5	0.79	
Freshwater ecotoxicity	kg 1,4-DB eq	0.96	0.47	0.36	
Freshwater eutrophication	kg P eq		0.51	0.088	
Marine eutrophication	kg N eq	0.11	0.054	0.16	0.030
Urban land occupation	m^2a	0.026	0.0088	0.019	0.004
Natural land transformation	m^2	0.015	0.011	0.03	0.01
Ozone depletion	kg CFC-11 eq	4.8E-5		6.2E-5	7.8E-6

10. INDUSTRIAL SYMBIOSIS: A PRACTICAL MODEL FOR PHYSICAL, ORGANIZATIONAL AND SOCIAL INTERACTIONS

Romain Sacchi, Arne Remmen

1. Introduction

An early analysis of industrial symbiosis (IS) in the scientific literature presented the analogy between human-made manufacturing systems that cooperate on the exchange of resources to a mutually beneficial end and cyclic organization patterns found in biological systems (*Hardy and Graedel, 2002; Chertow and Ehrenfeld, 2012; Harris 2007)*. IS is defined as a series of bilateral collaborations between industries as a response to environmental and regulatory changes in an effort to avoid waste disposal costs *(Desrochers, 2001)*. These collaborations mostly involve the reuse of water, waste, and the sharing of infrastructures. Economic and environmental benefits are documented in numerous cases, some of which were enumerated by Chertow (2007). IS is a central topic for the Industrial Ecology (IE) community and is recognized in national and European programs as the best available practice for managing waste *(Laybourn and Lombardi, 2012)*. A prominent case of IS is found in Kalundborg, Denmark, as described in the 1990s in the Journal of Industrial Ecology and the Journal of Cleaner Production *(Yu et al., 2014)*, although the first synergies appeared in the 1960s *(Jacobsen, 2006)*. Other cases have been documented with varying degrees of achievements and in different political and geographical contexts. Classifications of IS configurations range from self-organizing networks to centrally-planned eco-industrial parks (EIP).

The environmental benefits of IS were first described by applying tools such as the Mass Flow Analysis *(Sendra et al., 2007)* and Life Cycle Assessment *(Qiang et al., 2011; Kullapa and Amy, 2011; Laura et al., 2011; Tuomas et al., 2010; Hashimoto et al., 2010)*. Later, the focus shifted to the roots of IS related to economic and physical driving forces: scarcity of materials, physical proximity, environmental regulation, etc. *(Yu et al., 2014)*. To promote and institutionalize IS, some authors recommended considering social and organizational driving forces. Indeed, despite favorable economic and physical conditions, the same authors concluded that a lack of social cohesion and inadequate organization often prevent IS initiatives from reaching a mature and self-sustainable stage (*Hewes and Lyons, 2008; Paquin and Howard-Grenville, 2012; Lombardi and Laybourn, 2012; Jacobsen, 2006)*. A similar observation was made by *Chertow and Ehrenfeld (2012)* when they compared the development of self-organizing and planned industrial parks. The involvement and willingness of industries often lack in planned initiatives, which is detrimental to the project. The theory of networks and the importance of embeddedness were recognized by *Baas and Huisingh (2008)*, and aspects such as cognitive, cultural, spatial, and political shared values have been explored in recent works *(Paquin and Howard-Grenville, 2012; Lombardi and Laybourn, 2012)*. A broader definition of IS is becoming more common due to knowledge of the interactions beyond the resource flows and a focus on a more practical approach, such as was provided by *Lombardi and Laybourn (2012)*.

In parallel, Chertow observed a three-step development pattern among known examples of IS: sprouting, uncovering, and institutionalizing *(Chertow, 2007)*. According to her work, several cases of IS exist in which isolated symbiotic synergies "sprout" without any interrelated patterns. The cases have been investigated to increase public awareness as well as to create a network consciousness and encourage further developments. *Schwarz and Steininger (1997)* reported that in the case of Kalundborg, ten synergies unfolded in the 1961-1989 period, while six additional synergies appeared the next five years after the system had been "uncovered" in 1990. At a later stage, supporting institutions fostered the development of the network and provided companies with a common communication and expertise platform in the institutionalizing stage. IS networks found in Kalundborg, Kwinana, Styria, and Guayama have followed this development pattern and are now examples of complex and institutionalized IS. Region-wide systems found in the United Kingdom also have a coordinating organization: National Industrial Symbiosis Program (NISP).

In light of these conceptual understandings, the development of an IS system must include social and organizational interactions. In addition, IS practitioners need down-to-earth models that can be applied to further develop a sprouting IS case or to further uncover and institutionalize IS. In this regard, the model developed aims to capture and present the relationships of physical, organizational, and social characteristics identified in successful cases of IS. The model also indicates ways to assess their presence and enhance the identified mechanisms. According to the work of Marian Chertow, identifying missing mechanisms and enhancing existing ones should help IS practitioners bring industrial areas from a "sprouting" to an "uncovering" stage. After presenting the model, the next steps that IS practitioners can take are discussed, especially for strengthening the social mechanisms.

2. Method

A model based on observations lists IS facilitating mechanisms within the physical, social, and organizational realms of the reference cases: Kalundborg in Denmark, Kwinana (Australia), Styria (Austria), Guayama (Puerto Rico), Rotterdam (the Netherlands), and Nikopol (former Soviet Union, now Ukraine).

Kalundborg is the primary case, as it remains the most developed representation of IS. The reason for including a mechanism in the model was determined through empirical evidence. Literature and interviews in Kalundborg confirmed the relevance of a given mechanism in the model.

Interviews were conducted with initiators of the IS system in Kalundborg: Jørgen Christensen, former Vice-President of Novo Nordisk, and Valdemar Christensen, former Production Manager at the Asnæs power station, now DONG Energy, and later Chairman of Kalundborg's technical committee. These interviews were conducted in 2010. Interviews with persons currently involved were conducted in 2016, such as Peder Andreas Mathiesen, manager of Environmental Operations at Novozymes; Sven-Ole Toft, Business Developer at the oil refinery plant Statoil; Lisbeth Randers, Project and Development Manager in Kalundborg; Hans-Martin Møller, director of the utility company Kalundborg Forsyning; Jane Hansen, former coordinator at the Institute for Industrial Symbiosis until 2012 (now the Danish Industrial Symbiosis Center), and Mette Skovbjerg (current Director of the Danish Symbiosis Center).

The presence or absence of facilitating mechanisms was identified in the secondary IS cases through supporting literature. Secondary cases were chosen for their similarities to the Kalundborg case, though they differed in other aspects. Guayama is also located by the sea with an equivalent area size. Its industrialization began in the 1960s, and synergies arose due to sharing steam, hot water and wastewater, which were mostly based on decisions made by the local companies *(Chertow et al., 2008).* The case of Kwinana has a comparable level of diversity of synergies, as reported by *Beers et al. (2007a)* and *Harris (2007),* with a different organizational setting: a centralized planning policy. The IS case of Styria has common "waste receptors" (power plants, wastewater treatment plants, and residues feeding cement plants) and similar waste-related regulations (e.g., high waste disposa l costs), and its industrial network was detailed by *Schwarz and Steininger (1997).* The IS in Rotterdam Europoort is centered on the harbor and was initiated with the Kalundborg case in mind. The evolution of the organization is documented in *Baas (1998, 2008)* and *Fresner and Sage (2010).* As in Kalundborg and Styria, it operates a central district heating system, although the use of district heating is common and not the result of developed IS systems. Finally, for the IS case in Nikopol in the former Soviet Union, which was documented by Sathre and Grdzelishvili (2006), the complete state ownership allows for comparing and contrasting it with the other cases.

A physical mechanism is included in the model when its realization improves the feasibility of IS at an engineering level. Mechanisms at the inter- and intra-firm organizational levels are considered relevant when they facilitate operations and business relations among stakeholders. Finally, social mechanisms are confirmed when they improve cohesion, trust, and familiarity between stakeholders.

3. Analysis

Table 10.1 List of the physical mechanisms leading to IS development

Cause	Mechanism	Effect(s)	Indicator(s)
Municipality support	Flexible urban local plan	Installation of infrastructures	Visibility of industrial activities
Scarcity of resources (fresh water, mineral material, fossil fuels)	Accessibility to resources	Sourcing alternatives	Environmental configuration of the area
Ban against landfill of organic waste	Regulations	Full reuse of organic waste	Current environmental regulations
Flexible regulation in regards to waste handling		Freedom of action	Extent of the liability of the waste emitter
Short distance between companies	Proximity	Increased physical feasibility	Mean distance between the farthest located companies
Advanced technologies	Technical changes	Increased diversity of synergies	Total factor productivity
Diversity of industries	Complementarity	High number and variety of synergies	Presence of compatible waste receptors

Source: Author's own elaboration

3.1. Physical Sphere

3.1.1. Accessibility to Resources, Regulations, and Flexible Urban Plans

Limited access to resources and environmental pressure are often departure points for IS, such as in 1961 in Kalundborg, where the use of scarce groundwater was replaced by surface water for industrial use. Furthermore, the local oil refinery plant was not allowed to release its cleaning water back to where it was initially pumped. The solution was to reuse it along with wastewater from the power plant as cooling water and to avoid the use of seawater that could cause corrosion. Twenty years later, the power plant sent co-produced steam to the heating system in the municipality to sustain the anaerobic reactors of the enzymes producer, covering 50% of the needed energy input in total. A substantial part of the remaining cooling water was used in a fish farm at that time, which led to a 15% fish production increase *(Jacobsen, 2006)*. Novozymes also co-produce phosphor-rich biomass used as fertilizer in nutrient-poor areas in South-eastern Denmark *(Mathiesen, 2010)*. The lack of groundwater and the vulnerability of the local aquatic ecosystems led to this cascading reuse of freshwater *(Christensen, 2010a)*.

In parallel, high treatment costs and quality requirements for industrial water effluents recently led the utility company to conduct a demonstration project to use wastewater as a medium to grow micro-algae. The algae is fed by the nitrates and phosphorous-containing sludge stream from the biomechanical oxidation of the wastewater, thereby offering a viable treatment option for this secondary effluent while co-producing valuable proteins and possible biogas, according to *Møller (2016).* In Guayama, halogenated solvents were found in wells co-located nearby a pharmaceutical firm, and this led local managers to find a solution together, which increased the level of cooperation between them *(Chertow et al., 2008).*

Companies do not always include pressure and threats in their business strategies. Fiscal instruments palliate the problem. In Rotterdam, environmental taxes have minimized the use of rare materials and fostered synergies to reduce the consumption. Regulations that restrict air and water emissions also provide incentives for synergies. As documented in *Chertow and Lombardi (2005),* the power plant in Guayama is able to use wastewater from the co-located waste-water treatment plant, which leads to a significant reduction of SO_2, NOx, and PM10 emissions, granting it a license to operate. In addition, high landfill fees on solid waste fostered IS synergies (Christensen, 2010b). The complete ban on the landfill of organic waste was a strong incentive for Novozymes to find disposal alternatives for its by-products, which are currently reused as animal fodder and synthetic fertilizer substitutes *(Mathiesen, 2010).* Public regulations can reflect concerns stemming from material scarcity and environmental concerns, and then flexibility regarding the specific solution should be left to the companies, as witnessed in Kalundborg according to *Christensen (2010b).* In Rotterdam, IS actors were allowed to be "creative" to find alternative disposal means as long as their goals were in line with the overall regulations of the region (*Baas, 2008). Chertow (2004)* also reported that in the U.S., the law's regulation of waste leaves little opportunity for by product reuse as feedstock and raises problems of legal liability for the companies involved. Similarly, a strong regulation of inorganic waste materials limits the potential for producing alternative fuels in Kwinana *(Beers et al., 2009),* which leads to unused stockpiles of valuable mineral residues.

Resource scarcity, regulative instruments, and a relative legislative freedom are not always enough. The municipality must also support the idea and the necessary infrastructure. Out of more than fifty on-going synergies in Kalundborg today, at least one-third represents exchanges of water, steam, and heat through pipes. These pipes require resources when implemented and maintained as well as spatial planning because they can cross roads, open fields, and public spaces. A flexible urban local plan is a prerequisite. In Kalundborg, the municipality considers IS an opportunity; however, the involvement of the municipality was limited in the beginning, as Jørgen *(Christensen, 2010a)* stated that the IS was made by industries and that the municipality was not involved. Randers (Randers, 2016) stated that in the 1960s, various efforts were made without an understanding of IS, but the municipality was rather accommodating through the delivery of permits for the construction of infrastructures and the involvement of the municipality-owned utility company to distribute steam and water. Today, the Business Council of the municipality and the Danish Symbiosis Center (DSC) are far more supportive of IS and play more active roles. The municipality views IS as a means to increase productivity in companies and reduce their production costs via sharing resources, such as heat, water, and knowledge. In addition, this helps to preserve employment in the area and attract new companies *(Randers, 2016).*

3.1.2. Proximity

Physical proximity is an important part of IS, and all major cases of IS exhibit dense industrial areas; however, this does not hinder the realization of region-wide synergies. The short distance between companies in Kalundborg allowed for building infrastructures and identifying new synergies. The density of an industrial area can be determined by calculating the mean distance between the most remotely located companies. In Kalundborg, a mean distance of 2.6 km separates the most distantly located companies. The entropy and the distance of infrastructures influence the economic feasibility of residual energy exchanges *(Christensen, 2010a).* The distances between synergies are based on the cost of infrastructures and the return on investment. Kalundborg has a return on investment after three to four years *(Christensen, 2010a),* which is inferior to five years in all other cases according to *Toft (2016).*

3.1.3. Technical Progress and Complementarity

Continuous technical change over time leads to more diverse synergies. New technologies allow for using a higher fraction of solid and energy residual streams for a wider range of applications *(Christensen, 2010b).* In Rotterdam, some synergies rely on new technologies, such as the heat distribution system (Baas, 2008). In Kalundborg, high temperatures (around 90 °C) were initially required to operate heat exchanges from steam and cooling water. Technical progress allowed for the use of lower temperatures for a more diverse range of applications, e.g., to create mesophilic conditions for enzyme growth. Another example, which is the vertical reactors for the cultivation of micro-algae from the industrial water effluents of Kalundborg, allows for the process to become financially-feasible and space-efficient. In Kwinana, technical progress caused some synergies to stop because the amount of waste was reduced to an extent that does not justify its exchange or because the adoption of new production processes prevents the reuse of the by-product.

The variety and number of synergies in Kwinana (forty-seven) are due to a diverse blend of key processing industries. The diversity in synergies is usually correlated to the diversity of industrial sectors. *Chertow et al. (2008)* considered complementarity and variety key aspects in identifying input-output matches. Unlike Kwinana, the Rotterdam case illustrates a sectorial barrier with the formation of several clusters in the area with a low sectorial diversity and a high degree of competition. Low industrial diversity may also impede intimacy and trust and may lead to issues of business confidentiality between potential actors.

The presence of complementarity can be difficult to assess. A first step is to identify the "traditional waste receptors" *(Schwarz and Steininger, 1997)* that are present in all IS cases analyzed. Power plants and cement producers play major roles in Kalundborg, Kwinana, and Guayama, and steelworks play an important role in Nikopol. They usually complement each other's needs for energy and material inputs, leading to long-term exchanges of by-products. The presence of technological progress can be approximated by comparing the level of technological investments to the industry branch average. Another approach is to assess the evolution of the total-factor productivity (TFP) over time that accounts for the growth in production and that is not induced by an increase in capital or labor inputs. As suggested by *Ayres and Warr, (2005),* the conversion of raw energy inputs can be measured into useful physical work, such as exergy, while labor and capital inputs remain unchanged; however, this implies access to production data.

The organizational aspects define the extent to which IS utilizes new ideas and potential and adapts to changing frame conditions.

3.2. Organizational Sphere

Table 10.2 List of organization-related mechanisms leading to IS development

Cause	Mechanism	Effect(s)	Indicator(s)
Reduced virgin material use, avoided disposal	Economical profitability	Cost saving and income generating synergies	Presence of disposal fees, price of rare materials
Stakeholder driven interests	Governance	Dynamic changes, eased communication	Network collaborations
Suggestions from employees	Participatory management	Innovative ideas	Presence of quality, environment, or energy management systems
Need for centralized overview	Common communication platform	Bilateral agreements	Presence of coordinating body
Pipeline producers	Availability of infrastructure	Increased technical and economic feasibility	Presence and number of suppliers

Source: Author's own elaboration

3.2.1. Economic Profitability and Governance

Companies in Kalundborg were found to be more sensitive to economic benefits and returns on investments than to environmental protection initiatives *(Mathiesen, 2010)*. The economic profitability of a synergy can be ensured by landfill fees for waste or the scarcity of a particular material, which means the use of a more abundant by-product will result in cost savings.

Rotterdam encountered a time-related barrier when developing the exchange of heat between the power stations and the manufacturing units. Although the project was deemed economically viable, the payback period was beyond the traditional business time scope, especially due to the privatization of the power stations *(Baas, 2008)*. As in Kalundborg, a synergy must be economically profitable in the short-term *(Christensen, 2010a)*. *Jacobsen (2006)* also mentioned indirect economic benefits, such as flexible and safer sourcing of materials. This is usually considered part of the strategic vision of the company, which contrasts with the short-term profitability as specified in three-to-five-year contracts. This did not hinder investments in heat and steam exchanges of approximately 60 million USD in 1994 in Kalundborg, and the expected return on investment was 120 million USD *(Schwarz and Steininger, 1997)*. The investments are secured by contracts that specify transaction prices, quality requirements, etc. *Schwarz and Steininger (1997)* reported the existence of jointly-owned ventures between two companies for waste exchange operations to preserve both parties' interests. *Chertow and Lombardi (2005)* also reported economic profitability in the case of Guayama as a strong driver: the trade of steam between the coal power plant and the oil refinery plant generates an annual economic value greater than 8 million USD. In Nikopol, synergies were developed regardless of the market value of the waste. The economic sustainability of a given operation was not considered, and in some cases, significant resources were invested in reusing a by-product for which the demand was weak or the availability of a substitute was important. This led to situations in which the avoided environmental impacts following the reuse of a by-product did not justify the resources invested *(Sathre and Grdzelishvili, 2006)*.

The economic profitability for the company is, in the case of a self-organizing network, also based on a limited intervention of public authorities. In Kalundborg, IS has mostly been driven by market forces and initiatives from companies, where public influence had "little to say" *(Christensen, 2010a)*. The synergies develop according to market signals (material scarcity, oil price peaks, etc.), and the companies adapt accordingly. Yet, the absence of public interests is not desirable, either, because markets fail to encompass environmental externalities in the pricing information. Therefore, public intervention through environmental taxes, regulations, and organizational support can be a driver. In Kalundborg, public interventions have changed from being top-down and rule-based toward a more negotiated and "suggestion-based" method with a higher degree of flexibility over time. This is promoted by the DSC *(Skovbjerg, 2016)*, where the idea of a potential partnership is suggested rather than forced and where the ownership of the idea is gradually appropriated by the companies. In other words, there is a shift from interventions to facilitation and governance between the stakeholders. This also includes a common communication platform (see next section). In contrast, the IS case of Kwinana highly benefited from strong public organizational involvement as well as the research initiatives of Curtin University.

Clubs and interest organizations may also play roles in IS. In Kalundborg, the Environmental Club was established in 1989 as a network under the Business Council to ease communication between actors in the industrial area. The municipality, the Danish Society for Nature Conservation (Danish NGO), and companies were part of that club *(Christensen, 2010b).* The involvement of the "civil society" in general (defined in its broad sense by *Zadek, 2001),* as organized groups of consumers, residents, investors, NGOs, etc., could also play roles in the development of IS, but unfortunately, the impact on the outcomes has generally been ignored by the literature *(Yap and Devlin, 2016).*

3.2.2. Bottom-Up Participatory Management and Common Communication Platforms

At a company level, a participatory strategy allows engineers and technicians to express ideas as a way to identify new synergies because they have the technical background needed for the analysis *(Kørnøv et al., 2005).* Involving employees encourages suggestions for synergies supported by engineering analyses, where companies retain ownership of the idea. This type of management is observed within companies in Kalundborg. Novozymes, as other Danish companies, maintains close employee-manager relationships referred to as a "flat organizational structure" *(Mathiesen, 2010).*

At the project level, Rotterdam reported some difficulties for the coordinating actor Deltalinqs to integrate external actors to benefit from other perspectives *(Baas, 2008).* The member companies did not perceive the advantage of this approach. The companies and other involved actors maintain the "ownership of the synergy idea" *(Christensen, 2010a),* and again, bottom-up management is preferred to central planning, where synergy ideas come from companies themselves acting in their own interests. The same issue was reported by *Sathre and Grdzelishvili (2006)* in the Ukraine, where distant decision-makers did not have full knowledge of the local conditions (e.g., type of waste available), and the decision of reusing a by-product was not conditioned by its market value but by planning policies higher up in the hierarchy.

Governance also involves a coordinating body that may create a common communication platform. In Kalundborg, the Danish Symbiosis Center and part of the Municipal Business Council act as an overall coordinating body and communicate knowledge of IS outside the area. The role of ensuring internal communication between the IS members is held by the Industrial Symbiosis Association, of which the DSC is a member alongside the active companies of the IS network. Since "communication is more important than technology" *(Christensen, 2010a),* the DSC coordinates joint efforts, maps the waste flows, and suggests possible matches between members to the Industrial Symbiosis

Association for assessment *(Skovbjerg, 2016).* The Industrial Symbiosis Association partly funds the DSC, which acts as a contact point, organizes visits, and disseminates knowledge about IS.

The case of Kwinana underlines the role of a coordinating body as a means to foster interactions between member companies. In Rotterdam, the ROM-Rijnmond (Spatial Planning and Environmental Organization) project committee plays this role. Although the roles of Kwinana and Rotterdam's coordinating bodies seem stronger than in Kalundborg, the aim to enhance communication between the companies through a communication platform appears common. These two mechanisms are mostly identified and evaluated through field visits and interviews with managers and employees. The use of management systems, such as ISO 9001 and ISO 14001, can be seen as an indicator for systematic management with a focus on continuous improvements of quality and environmental performance.

3.2.3. Availability of Infrastructures

Different types of infrastructures ensure a circulation of flows between companies. Roads, utility pipelines, heat exchangers, and cooling systems are examples. These infrastructures must be available and must work properly to achieve IS synergies *(Côté and Cohen-Rosenthal, 1998).* The proximity of infrastructure suppliers is relevant, but engineers with the necessary knowledge to create, operate, and maintain these infrastructures has proven to facilitate the establishment of "linkages" between companies. Kwinana presents numerous specific facilities that foster the diversity and feasibility of synergies: two wastewater treatment plants and two cogeneration plants. In Rotterdam, the cost of infrastructures (steam pipes) initially impeded the development of IS synergies *(Baas and Huisingh, 2008).*

3.3. Social Sphere

Table 10.3 List of the social mechanisms leading to IS development

Cause	Mechanism	Effect(s)	Indicator(s)
Transparency	Transfer of information	Overview of possible synergies	Existence of flow maps
		Trust between managers	Knowledge of each other's activities and inputs/outputs
Mental proximity	Social interactions and trust	CEOs know each other	Extra-professional interactions
Networking	Willingness	Time and resource investment	Participation in IS workshops and other events
Knowledge of IS			
Separate industrial area	Intimacy	Bilateral agreements	Presence of competition
		Good collaboration	

Source: Author's own elaboration

The social dimension of the overall model encompasses social and human actions that enhance the development of mechanisms such as trust and willingness to support IS synergies. This is highlighted in the table above.

3.3.1. Transfer of Information and Social Interactions

Social interactions are key mechanisms when developing common interests, trust, and commitment between the members of a network. *Christensen (2010a)* explained that companies are not forced to cooperate with each other. Economical profitability may motivate cooperation, but it does not prevent risks that relate to confidentiality issues *(Beers et al., 2007a)*. A bilateral agreement on resource exchange implies information on the production processes involved, the waste quantity and quality, etc. These data represent sensitive information that might put companies at risk if disclosed to competitors; however, social interactions can lead to trust, communication, and mental proximity. This is also the case when considering the specific waste being exchanged: "communication and trust are thought to be important (…) when the materials being exchanged have potential liabilities because they are subject to environmental regulations" *(Chertow, 2004)*. Also, physical proximity between companies in Kalundborg has led to social interactions and "mental proximity" *(Christensen, 2010a)*. In Kalundborg, the management functions of a growing number of companies tend to be located away from the production sites, and the managers meet less frequently. This is considered a potential obstacle to intimacy, trust, and the exchange of ideas *(Skovbjerg, 2016; Toft, 2016)*.

Trust and mental proximity ease information exchanges between actors of IS. The importance of mapping material and energy flows within an area to assess potential synergies has been emphasized *(Chertow, 2007)*. Beginning in 1995, manufacturing companies in Denmark must report resource inputs and outputs to the authorities, and these reports are helpful; however, a full Material Flow Analysis (MFA) of the industrial area would provide a more comprehensive picture of matchmaking possibilities. In any case, companies must agree to disclose input and output data. In Kalundborg, Kwinana, and Rotterdam, the coordinating body has the responsibility of this task. Ultimately, the presence of trust and mental proximity is needed to obtain a complete overview of the system.

3.3.2. Willingness and Intimacy

When implementing IS, willingness to cooperate through synergies is a prerequisite, which can create awareness of IS benefits, shared technical knowledge, economic perspectives, trust, and communication with one another. Decision makers must be willing to participate in such collaborations *(Christensen, 2010a)*.

Knowledge sharing and common understanding contribute to building trust between actors. Close and social relationships are favorable when sharing vital information about activities and performances of the single companies, and this can appear in a town with a limited industrial area. Kalundborg is nevertheless the second-most industrially dense area after the Copenhagen region. A sufficient number of industries are present, but potential competitors are absent. The level of competition within Kalundborg is low, and it has diverse and complementary industrial branches. This is beneficial for intimacy, which plays an important role in the beginning of IS synergies *(Christensen, 2010a)*. When initiating the first synergies, most of the managers involved in IS shared common social activities *(Mathiesen, 2010)*. In contrast, a low degree of competition may also lead to difficult sourcing of a by-product from a single source: a situation of dependency and a price dictated by the waste emitter can put an end to cooperation *(Toft, 2016)*.

The IS case of Kwinana demonstrates the importance of intimacy. The limited competition between companies and the distance from other major industrial centers in Eastern Australia explain the mental proximity. *Paquin and Tilleman (2014)* suggested that companies are more likely to cooperate with other partners within the industrial sector. IS practitioners can assess the willingness and intimacy between companies by evaluating their knowledge with one another's activities and the level of personal acquaintance.

4. Results

The model depicted in Figure 10.1 is based on the analysis presented in the previous section. At the boundary of each sphere, mechanisms that are favorable to the establishment of IS are listed. The different groups of stakeholders and the dominant interactions between them are illustrated. Environment is understood as natural capital. Investors are the interest group behind investments in IS synergies, often the companies themselves. Coordinating body is the institution, either public or funded by the network, that coordinates tasks and communications. The external third party could be the IS practitioner who wishes to further the development of the network. This role is sometimes assumed by the coordinating body, as in Kalundborg. The Municipality is understood as the technical-environment committee and/or the urban committee of the city as well as the public authorities.

An equal importance of the different mechanisms is indicated in the model; however, this shows that successful examples of IS are characterized by social cohesion, favorable organizational settings, and physical configurations. The greyed one-way arrow indicates that the three dimensions are not only necessary but also that the extent of their presence will usually reinforce the presence of the other two. The physical realization of the synergy reinforces the presence of the needed social mechanisms to close the loop of the model by reinforcing trust *(Baas, 2008),* learning, and the acquisition of experience or realized gains *(Chertow et al., 2008).*

Most IS cases gained momentum due to environmental issues: pollution of the nearby water stream by release of cooling and cleaning water in Kalundborg *(Christensen, 2010a),* presence of halogenated solvents in wells in Guayama *(Chertow et al., 2008),* or a need to minimize impacts on marine ecosystems in Kwinana *(Beers et al., 2007b).* The environmental issue was the departure point for turning a potential environmental problem into a solution, where waste from one company became a resource for another. The authorities expected solutions to these problems. Material scarcity can also trigger IS when it directly threatens business perspectives. The exception is Nikopol, where IS was viewed as a means to increase production volumes via increased resource efficiency *(Sathre and Grdzelishvili, 2006).*

The absence of organizational and social mechanisms does not hinder the development of IS. Again, the IS case of Nikopol was driven by legitimate incentives but with a lack of knowledge of the local conditions, the exclusion of the local managers in the decision-making process, the disregard of market signals for by-products, and a lack of social cohesion, which led to sub-optimal decisions and short-lived development *(Sathre and Grdzelishvili, 2006).* Hence, awareness, trust, and willingness are viewed as important drivers when initiating IS.

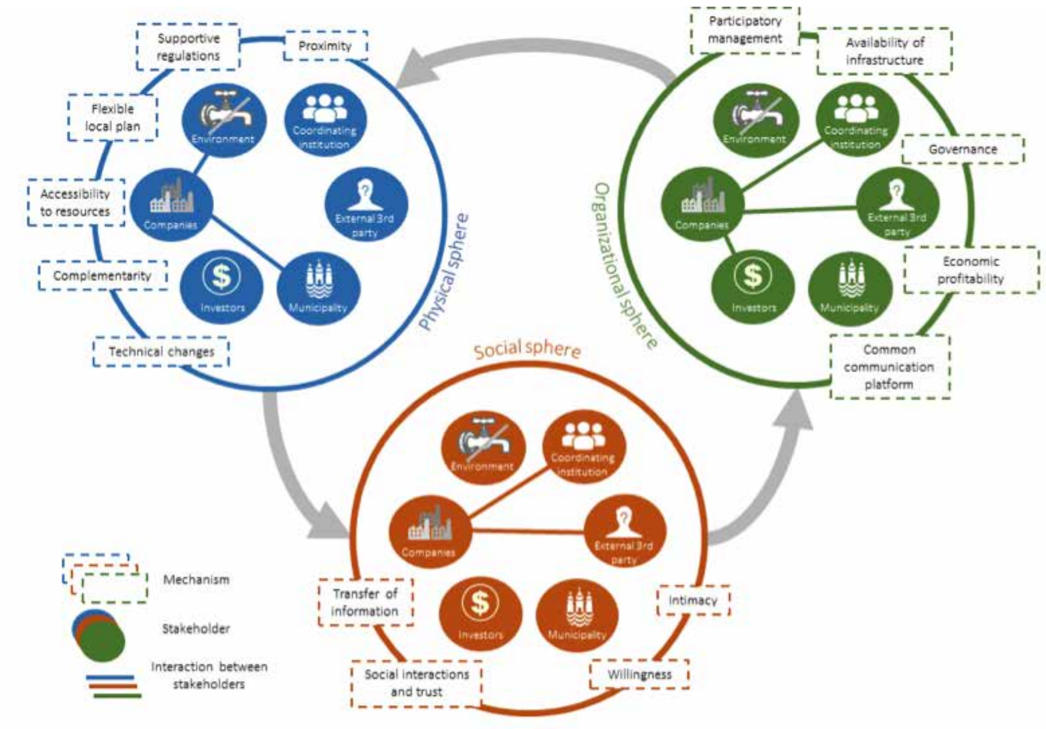


Figure 10.1 Social, Organizational, and Physical Dimensions of Industrial Symbiosis and Stakeholder Interactions
Source: Author's own elaboration

5. Next Steps in Uncovering Industrial Symbiosis

The model and the framework presented can be used by IS practitioners to uncover and develop further synergies. This can help assess the presence of mechanisms that facilitated IS in mature cases and help focus on the lack of mechanisms in other industrial areas. The approach chosen to further IS synergies can differ: companies have initiated some synergy projects, while planners have also designed entire eco-industrial parks. Regardless of the approach, assessing the presence of social facilitating mechanisms seems to be a useful first step. Among these mechanisms, awareness about IS, a willingness to invest, and trust between actors are paramount and have generally been referred to as social embeddedness in the literature *(Boons and Howard-Grenville, 2009; Doménech and Davies, 2011; Baas and Huisingh, 2008; Chertow and Ashton, 2009)*. They also appear to be linked to one another. Awareness can also lead to willingness and trust, and in that regard, different ways to increase awareness have been suggested from local introductory workshops *(Paquin and Howard-Grenville, 2012)* on interventions of IS champions (*Hewes and Lyons, 2008)* to documenting the actual existing synergies *(Chertow, 2007)*. Once awareness is gained, trust from the potential actors and willingness to invest can be obtained through demonstration projects, uncovering the existing synergies in the sprouting IS case, or presenting successful projects in an uncovered IS case.

6. Conclusions

Based on interviews and a literature review, the model presented lists mechanisms that have led to effects that are favorable to the development of synergies among the recognized IS cases of Kalundborg, Rotterdam, Kwinana, Styria, and Guayama. These mechanisms are distinctively placed in different dimensional realms along with ways to identify and measure them.

Within the physical dimension, environmental pressure is a mechanism that leads to innovative cost-saving and environmental safeguarding solutions. Indirect public interventions through regulations on the use of environmental resources are also needed. The cases also indicate the importance of the organizational dimension, e.g., that the intervention of public institutions should be limited to a "suggestion-based" governance approach in most cases, where support is advised and interactions in the network are facilitated but where companies remain owners of project ideas and management. In addition, participatory forms of management within companies help in gathering the technical knowledge to develop synergies. The social dimensions, such as intimacy, willingness, and transparency of information, act as the "glue" of IS, ensure the perennial development, and are considered of the utmost importance when initiating synergy projects. Willingness and trust may also be initiated through awareness. A major obstacle can be the centralization of the decision-making power to other locations in the headquarters that might have priorities other than the further development of IS.

7. Acknowledgments

The authors wish to thank Mette Skovbjerg, Director of the Danish Symbiosis Center, and Lisbeth Randers, Development and Project Manager at Kalundborg Municipality, as well as the other interviewees who helped in gathering the necessary information.

References

Ayres, R. U. and B. Warr. 2005. Accounting for growth: the role of physical work. Structural Change and Economic Dynamics 16(2): 181-209.

Baas, L. 1998. Cleaner production and industrial ecosystems, a Dutch experience. Cleaner production and industrial ecosystems, a Dutch experience.

Baas, L. 2008. Industrial symbiosis in the Rotterdam Harbour and Industry Complex: reflections on the interconnection of the techno-sphere with the social system. Business Strategy and the Environment 17(5).

Baas, L. W. and D. Huisingh. 2008. The synergistic role of embeddedness and capabilities in industrial symbiosis: illustration based upon 12 years of experiences in the Rotterdam Harbour and Industry …. The synergistic role of embeddedness and capabilities in industrial symbiosis: illustration based upon 12 years of experiences in the Rotterdam Harbour and Industry ….

Beers, D., A. Bossilkov, G. Corder, and R. Berkel. 2007a. Industrial Symbiosis in the Australian Minerals Industry: The Cases of Kwinana and Gladstone. Journal of Industrial Ecology 11(1).

Beers, V. D., G. Corder, and A. Bossilkov. 2007b. Industrial symbiosis in the Australian minerals industry. Industrial symbiosis in the Australian minerals industry.

Beers, V. D., A. Bossilkov, and C. Lund. 2009. Development of large scale reuses of inorganic by-products in Australia: The case study of Kwinana, Western Australia. Resources, Conservation and Recycling 53(7): 365-378.

Boons, F. and J. Howard-Grenville. 2009. Introducing the social embeddedness of industrial ecology. The Social Embeddedness of Industrial Ecology: 3-27.

Chertow, M. and J. Ehrenfeld. 2012. Organizing Self-Organizing Systems. Organizing Self- Organizing Systems.

Chertow, M. R. 2004. Industrial symbiosis. Industrial symbiosis.

Chertow, M. R. 2007. "Uncovering" Industrial Symbiosis. Journal of Industrial Ecology 11(1): 11-30.

Chertow, M. R. and D. R. Lombardi. 2005. Quantifying economic and environmental benefits of co-located firms. Quantifying economic and environmental benefits of co-located firms.

Chertow, M. R. and W. S. Ashton. 2009. The social embeddedness of industrial symbiosis linkages in Puerto Rican industrial regions. The social embeddedness of industrial symbiosis linkages in Puerto Rican industrial regions.

Chertow, M. R., W. S. Ashton, and J. C. Espinosa. 2008. Industrial Symbiosis in Puerto Rico: Environmentally Related Agglomeration Economies. Regional Studies 42(10): 12991312.

Christensen, J. 2010a. Interview with Jørgen Christensen, edited by R. Sacchi.

Christensen, V. 2010b. Interview with Valdemar Christensen, edited by R. Sacchi.

Côté, R. P. and E. Cohen-Rosenthal. 1998. Designing eco-industrial parks: a synthesis of some experiences. Designing eco-industrial parks: a synthesis of some experiences.

Desrochers, P. 2001. Cities and industrial symbiosis: Some historical perspectives and policy implications. Journal of Industrial Ecology 5(4): 29-44.

Doménech, T. and M. Davies. 2011. The role of embeddedness in industrial symbiosis networks: phases in the evolution of industrial symbiosis networks. The role of embeddedness in industrial symbiosis networks: phases in the evolution of industrial symbiosis networks.

Fresner, J. and J. Sage. 2010. Sustainable Development in the Process Industries: Cases and Impact. Sustainable Development in the Process Industries: Cases and Impact: 1-3.

Hardy, C. and T. E. Graedel. 2002. Industrial ecosystems as food webs. Journal of Industrial Ecology 6(1): 29-38.

Harris, S. 2007. The potential role of industrial symbiosis in combating global warming. International Conference on Climate Change.

Hashimoto, S., T. Fujita, Y. Geng, and E. Nagasawa. 2010. Realizing CO_2 emission reduction through industrial symbiosis: A cement production case study for Kawasaki. Resources, Conservation and Recycling 54(10): 704-710.

Hewes, A. K. and D. I. Lyons. 2008. The humanistic side of eco-industrial parks: champions and the role of trust. The humanistic side of eco-industrial parks: champions and the role of trust.

Jacobsen, N. 2006. Industrial Symbiosis in Kalundborg, Denmark: A Quantitative Assessment of Economic and Environmental Aspects. Journal of Industrial Ecology 10(1- 2): 239-255.

Kullapa, S. and E. L. Amy. 2011. Evaluating industrial symbiosis and algae cultivation from a life cycle perspective. Bioresource technology 102(13): 6892-6901.

Kørnøv, L., H. Lund, and A. Remmen. 2005. Tools for a sustainable development. Tools for a sustainable development.

Laura, S., L. Suvi, N. Ari, and M. Matti. 2011. Analyzing the Environmental Benefits of Industrial Symbiosis. Journal of Industrial Ecology.

Laybourn, P. and R. D. Lombardi. 2012. Industrial Symbiosis in European Policy. Journal of Industrial Ecology.

Lombardi, D. R. and P. Laybourn. 2012. Redefining industrial symbiosis. Redefining industrial symbiosis.

Mathiesen, P. A. 2010. Interview notes with Peder Andreas Mathiesen, edited by R. Sacchi.

Møller, H.-M. F. 2016. Interview with Hans-Martin Friis Møller, edited by R. Sacchi.

Paquin, R. L. and J. Howard- Grenville. 2012. The evolution of facilitated industrial symbiosis. The evolution of facilitated industrial symbiosis.

Paquin, R. L. and S. G. Tilleman. 2014. Is There Cash in That Trash? Is There Cash in That Trash?

Qiang, L., J. Peipei, Z. Jun, Z. Bo, B. Huadan, and Q. Guangren. 2011. Life cycle assessment of an industrial symbiosis based on energy recovery from dried sludge and used oil. Journal of Cleaner Production 19(15): 17001708.

Randers, L. 2016. Interview with Lisbeth Randers, edited by R. Sacchi.

Sathre, R. and I. Grdzelishvili. 2006. Industrial symbiosis in the former Soviet Union. Industrial symbiosis in the former Soviet Union.

Schwarz, E. J. and K. W. Steininger. 1997. Implementing nature's lesson: the industrial recycling network enhancing regional development. Journal of Cleaner Production 5(1): 47-56.

Sendra, C., X. Gabarrell, and T. Vicent. 2007. Material flow analysis adapted to an industrial area. Journal of Cleaner Production 15(17): 1706-1715.

Skovbjerg, M. 2016. Interview with Mette Skovbjerg, edited by R. Sacchi.

Toft, S.-O. 2016. Interview with Sven-Ole Toft, edited by R. Sacchi.

Tuomas, J. M., P. Suvi, and S. Laura. 2010. Quantifying the total environmental impacts of an industrial symbiosis - a comparison of process-, hybrid and input-output life cycle assessment. Environmental science & technology 44(11): 4309-4314.

Yap, N. T. and J. F. Devlin. 2016. Explaining Industrial Symbiosis Emergence, Development, and Disruption: A Multilevel Analytical Framework. In Journal of industrial Ecology.

Yu, C., C. Davis, and G. P. J. Dijkema. 2014. Understanding the evolution of industrial symbiosis research. Understanding the evolution of industrial symbiosis research.

Zadek, S. 2001. The civil corporation: the new economy of corporate citizenship. Edited by Earth-Scan. London.

This digital publication was completed on August 2017.
Edition and design were in charge of:
Luis Eduardo Velazquez Contreras

"El saber de mis hijos
hará mi grandeza"