CRANFIELD UNIVERSITY

MÉLANIE DESPEISSE

SUSTAINABLE MANUFACTURING TACTICS AND IMPROVEMENT METHODOLOGY: A STRUCTURED AND SYSTEMATIC APPROACH TO IDENTIFY IMPROVEMENT OPPORTUNITIES

SCHOOL OF APPLIED SCIENCE

PhD THESIS
Academic Year: 2010 - 2013

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This thesis is submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy

ABSTRACT

Growing environmental concerns caused by increasing consumption of natural resources and pollution need to be addressed. Manufacturing dictates the efficiency with which resource inputs are transformed into economically valuable outputs in the form of products and services. Consequently it is also responsible for the resulting waste and pollution generated from this transformation process.

This research explored the challenges faced by sustainable manufacturing as a concept and as a model for manufacturing systems. The work is strongly based on the concepts of sustainability and industrial ecology applied at factory level. The research objectives were to understand what companies are doing to improve their sustainability performance at operational level (resource productivity) and to help other companies repeating such improvements in their own factory. In other words, the aim is to generalise sustainable practices across the manufacturing industry.

The work started with a review of existing theories and practices for sustainable manufacturing and other related fields of research such as industrial ecology, cleaner production and pollution prevention. The concepts, themes, strategies and principles found in the literature provided a strong foundation to approach resource productivity improvements. The industrial cases collected gave an insight into the application of these strategies and principles in a factory. From the analysis of existing theories and practices, generic tactics were developed by translating 1000+ practices into generic rules and by mapping them against strategies and principles for sustainable manufacturing to check the completeness and consistency of the *tactics library*. To test the tactics and assist the user in their use through factory modelling, an *improvement methodology* was developed based on the same strategies and principles to provide a structured guide for accessing tactics and systematically identifying improvement opportunities. The research findings were tested with a series of prototype applications. These tests were carried out as part of a wider project (THERM). This project uses a modelling and simulation approach to capture the resource flows (material, energy, water and waste), the interactions within the manufacturing system (manufacturing operations, surrounding buildings and supporting facilities) and the influence of external factors' variation (weather conditions, building orientation and neighbouring infrastructures). The outcomes of the prototype applications helped develop and refine the research findings.

The contribution to knowledge of this research resides in bridging the gap between high-level concepts for sustainability and industrial practices by developing a *library of tactics* to generalise sustainable manufacturing practices and an *improvement methodology* to guide the tactics implementation. From a practical viewpoint, the research provides a structured and systematic approach for manufacturers to undertake the journey towards more sustainable practice by improving resource flows in their factory.

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LIST OF PUBLICATIONS

Despeisse, M., Ball, P. D., Evans, S. and Levers, A. (2009), "Zero Carbon Manufacturing through Process Flow Modelling", *Proc. of the 11th Int. Conf. on Modern Information Technology in the Innovation Processes of the Industrial Enterprises (MITIP 2009),* 15–16 Oct. 2009, Bergamo (Italy), pp. 565.

Ball, P. D., Despeisse, M., Evans, S. and Levers, A. (2009), "Mapping Manufacturing Material, Energy and Waste Process Flows", Shunmugam, M. S. and Ramesh Babu, N. (eds.), in: *Proc. of the 7th CIRP Global Conference on Sustainable Manufacturing (GCSM 2009)*, 2–4 Dec. 2009, Madras (India), pp. 349.

Despeisse, M., Ball, P. D., Evans, S. and Levers, A. (2010), "Process Flow Modelling for More Environmentally Sustainable Manufacturing Operations", *Int. Conf. on Advances in Production Management Systems (APMS 2010),* 11–13 Oct. 2010, Como (Italy), pp. 1.

Despeisse, M., Ball, P. D. and Evans, S. (2011a), "Design of Tactics for Sustainable Manufacturing", Bártolo, H. e. a. (ed.), in: *Proc. of Sustainable Intelligent Manufacturing Conf. (SIM 2011),* 29 June–1 July 2011, Leiria (Portugal), IST Press, Lisboa, pp. 53.

Ball, P. D., Despeisse, M., Evans, S., Greenough, R. M., Hope, S. B., Kerrigan, R., Levers, A., Lunt, P., Oates, M. R., Quincey, R., Shao, L., Waltniel, T., Wheatley, C. and Wright, A. J. (2011), "Modelling energy flows across buildings, facilities and manufacturing operations", *Proc. of the International Manufacturing Conference (IMC28),* 30 Aug.–1 Sept. 2011, Dublin (Ireland), pp. 1.

Despeisse, M., Ball, P. D. and Evans, S. (2011), "Identifying improvement opportunities towards sustainable manufacturing", *Proc. of the International Manufacturing Conference (IMC28),* 30 Aug.–1 Sept. 2011, Dublin (Ireland), pp. 1.

Despeisse, M., Ball, P. D. and Evans, S. (2011b), "Modelling and Tactics for Sustainable Manufacturing: an Improvement Methodology", Günther, S. (ed.), in: *Proc. of the 9th CIRP Global Conference on Sustainable Manufacturing, Sustainable Manufacturing – Shaping Global Value Creation (GCSM 2011),* 28–30 Sept. 2011, Saint Petersburg (Russia), Technische Universität Berlin, Berlin, Germany, pp. 20.

Ball, P. D., Despeisse, M., Evans, S., Greenough, R., Hope, S., Kerrigan, R., Levers, A., Lunt, P., Oates, M., Quincey, R., Shao, L., Waltniel, T., Wheatley, C. and Wright, A. J. (2012), "Factory modelling: combining energy modelling for buildings and production systems", Emmanouilidis, C., Taisch, M. and Kiritsis, D. (eds.), in: *Competitive Manufacturing for Innovative Products and Services: Proc. of the Advances in Production Management Systems Conf. (APMS 2012),* 24–26 Sept. 2012, Rhodes (Greece) , pp. 1.

Oates, M. R., Despeisse, M., Ball, P. D., Evans, S., Greenough, R. M., Hope, S. B., Levers, A., Lunt, P., Quincey, R., Shao, L., Waltniel, T., Wheatley, C. and Wright, A. J. (2012), "Design of Sustainable Industrial Systems by Integrated Modelling of Factory Building and Manufacturing Processes", *Proc. of the 10th CIRP Global Conference on Sustainable Manufacturing - Towards Implementing Sustainable Manufacturing (GCSM 2012),* 31 Oct.–2 Nov. 2012, Istanbul (Turkey) , pp. 1.

Despeisse, M., Mbaye, F., Ball, P. D. and Levers, A. (2012), "The emergence of sustainable manufacturing practices", *Production Planning and Control,* vol. 23, no. 5, pp. 354-376.

Despeisse, M., Ball, P. D., Evans, S. and Levers, A. (2012), "Industrial ecology at factory level – a conceptual model", *Journal of Cleaner Production,* vol. 31, no. 3-4, pp. 30-39.

Despeisse, M., Ball, P. D., Evans, S. and Levers, A. (2012), "Industrial ecology at factory level – a prototype methodology", *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture,* vol. 226, no. 10, pp. 1648-1664.

Despeisse, M., Oates, M.R. & Ball, P.D. (2013), "Sustainable manufacturing tactics and cross-functional factory modelling", *Journal of Cleaner Production,* vol. 42, no. 1, pp. 31-41.

Despeisse, M., Ball, P.D. and Evans, S. (2013) "Strategies and Ecosystem View for Industrial Sustainability", Nee, A. Y. C., Song, B. and Ong, S. K. (eds.), in: *Re-engineering Manufacturing for Sustainability,* 17–19 April 2013, Singapore, Springer, Berlin, pp. 567.

CONTENTS

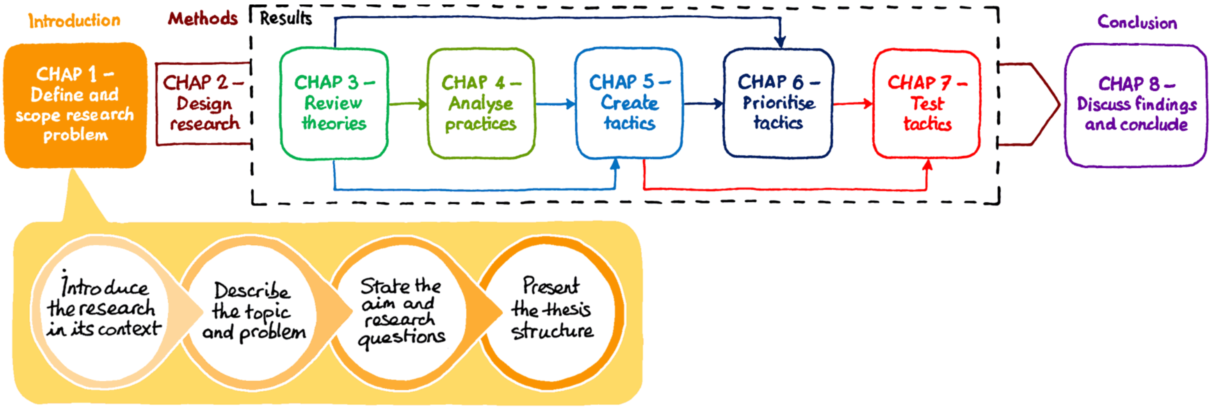
FIGURES AND TABLES

LIST OF ABBREVIATIONS

3Ps	People, Planet, Profit
3Rs	Reduce, Reuse, Recycle
6Rs	Reduce, Reuse, Recycle, Redesign, Remanufacture, Recover
ASH	Air Supply House
BOM	Bill of Materials
C2C	Cradle-to-Cradle
CO_2	Carbon dioxide
CP	Clean(er) Production
DfE	Design for the Environment
DfX	Design for Assembly/Disassembly/Recycling/ Remanufacturing/Recovery/etc.
ECM	Environmentally Conscious Manufacturing
HVAC	Heating, Ventilation and Air Conditioning
HX	Heat Exchanger
IE	Industrial Ecology
IT	Information Technology
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
MEW	Material, Energy, Water and Waste
MFA	Material Flow Analysis
NO_X	Nitrogen Oxide
P2	Pollution Prevention
PDCA	Plan-Do-Check-Act
PM	Particulate Matter
RF	Resource Flow
Rs	Typically the 3Rs strategies (Reduce, Reuse, Recycle), but can also include wider strategies (Reduce, Redesign, Reuse, Repair, Remanufacture, Reverse logistics, Recycle, Recover, etc.)
SMPs	Sustainable Manufacturing Practices
SO_X	Sulfur Oxide
$StRe^3TCh$	Stop, Remove, Repair, Reduce, Trade and Change
TC	Technology Component
THERM	THrough-life Energy and Resource Modelling
TMUK	Toyota Motor Manufacturing (UK)
VE	Virtual Environment
WCED	World Commission on Environment and Development

Chapter 1 INTRODUCTION

This introductory chapter presents the context and scope of this research and summarises current understanding of the environmental problems and proposed solution for society in general and for the manufacturing industry in particular. It then identifies and defines the specific subject area of interest: Sustainable Manufacturing. Finally the aim and research questions are discussed to highlight the importance of this research for industrial sustainability.



1.1 Background: the Sustainability Challenge

Society is facing a great challenge: shift to a sustainable mode of operation to meet human basic needs while preserving Earth's life support systems. Since the Industrial Revolution, technological development has brought tremendous improvements to our quality of life. But the way society operates is also leading to undesirable consequences for the planet, for people, and also for the economy.

Climate change is probably the most widely accepted issue (Intergovernmental Panel on Climate Change, 2007) that requires a dramatic shift in our way of living. However, the first warnings that our society was on an unsustainable path came earlier with Malthus' essay on population growth (Malthus, 1798), Carson's book *Silent Spring* about the use of "biocides" (Carson, 1962), and the Club of Rome's well-known report *Limits of Growth* on resource depletion (Club of Rome and Meadows, 1972).

Atmospheric pollution, accumulation of waste and pollutants in soil and water, heavy usage of toxic substances, resource scarcity, threats to wildlife as well as human health, and many other visible signs are demonstrating that society is not operating sustainably and that the next generations will struggle to get the same level of life standard (Ausubel and Sladovich, 1989; Grübler, 2003; Ponting, 2007). The recent economic upheavals, increasing material and energy prices are other unsustainability symptoms which businesses must fight against to survive and remain profitable (Pezzoli, 1997). Finally, the growing societal problems of hunger and poverty, inequities at national and international scale, population growth and associated increase in demand for products while reaching the limits of Earth's carrying capacity are also showing the continuous failure of society to provide sustainable, healthy and enjoyable life standard for all.

Sustainable development has been defined as "meeting the needs of the present without compromising the ability of future generations to meet theirs" (World Commission on Environment and Development, 1987). This concept has been formulated as the solution for decoupling economic development and environmental impact while generating fairly-distributed wealth. This theoretical solution is now well-established and widely accepted by governments and companies. The motivations and pressures for industry to become more sustainable are coming from governmental measures at regional, national and international levels in the form of regulations, taxes and penalties for lack of compliance; from economic incentives due to increasing costs linked to resource scarcity and waste disposal; from stakeholders whose growing interest in ethical and environmental issues is affecting decision-making; from consumer awareness which contributed to the current shift in market environment as competitive advantage and market share can be gained through more ethically and environmentally responsible practices.

Industry and technology are traditionally associated with negative impacts on the natural environment. But they are increasingly considered as part of the decoupling equation for sustainability (Ehrlich and Holdren, 1971; Gray, 1989). Industrial activities represent a significant share of anthropogenic GHG emissions causing global warming, sea-level rise and ocean acidification. Moreover resource scarcity is also putting constraints industrial systems (Frosch and Gallopoulos, 1989). With the need for sustainability now widely recognised as a great challenge for society, industrial companies have become part of the solution to change the way society operates (Erkman, 1997; Jovane et al., 2008). Solutions such as low-carbon and renewable energy sources (Grubb, 1997; Dovì et al., 2009) as well as green innovation, sustainable product and clean technologies (Kemp and Soete, 1992; Montalvo, 2008) have gain greater attention.

However, renewable energy source and technology alone will not be sufficient to mitigate the negative effects of climate change. The journey towards sustainability will take much wider changes involving the whole society and a large collection of topics and perspectives on the various sustainability issues society is facing. Figure 1.1 shows the main topics and perspectives that compose the big picture for industrial and societal sustainability.

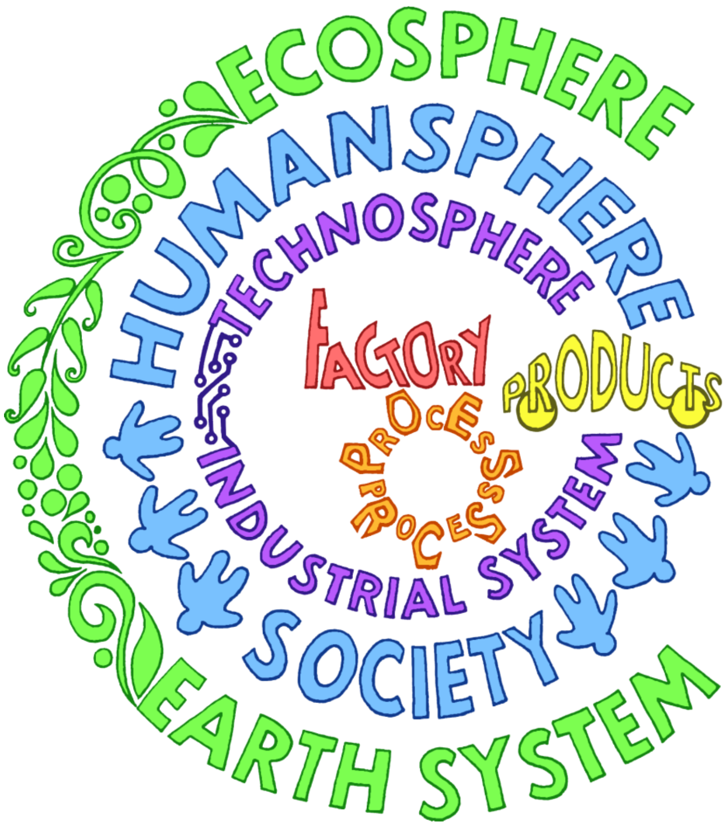


Figure 1.1. Perspectives for industrial sustainability
Adapted from (Despeisse et al., 2013)

1.2 Topic: Sustainable Manufacturing

The first challenge encountered when studying *sustainable manufacturing* is its definition. *Sustainable development* is now a well-established concept (Lélé, 1991; Stern et al., 1996; Robèrt et al., 2002; Robinson, 2004). But less obvious is the definition of *sustainability*. Many authors are proposing different definitions based on their own understanding and belief of what a sustainable level of activity is for a company, for a region, for industry in general, or for society as a whole.

Sustainable development was introduced as an approach to sustainability. A widely-accepted definition is the one proposed in the Brundtland report *Our Common Future* (World Commission on Environment and Development, 1987). Another definition which might be closer to quantify what a sustainable performance is has been proposed by Robèrt in the *Natural Step* with the four systems conditions to better manage the resource flow exchange between industrial and natural systems (Robèrt, 1996). A similar but simpler definition was proposed by Ricoh: “We need to reduce the environmental impact of mankind's economic activities to a level that the Earth's self-recovery capabilities can deal with” (Ricoh, 2011). . This idea of better aligning man-made resource flows (technical materials) and natural resource flows (biological materials) has been captured by in the circular economy (Ellen MacArthur Foundation, 2013). These definitions highlight the need to adjust the level of performance to Earth’s carrying capacity to generate resources and assimilate waste and pollutant emissions.

Industry clearly has a role to play in sustainable development as it is responsible for the creation of products and services that improve life standard and create wealth. It is also responsible for the same problems it is now fighting to remedy: industrial activities have traditionally been associated with resource depletion and pollution. This is a dilemma faced by technological systems, or the so-called environment-technology paradox (Gray, 1989). The role of manufacturing is clearly fundamental to achieve a sustainable level of performance. Industry and technology are determining the resource productivity of the technosphere (Sarkis, 2001; Seliger et al., 2008) and manufacturing is a responsible for life cycle phase where resources are transformed into economically valuable goods.

In other words, technology is responsible for the efficiency with which it transforms natural resources into economically valuable goods and improving social welfare. Responsible business practice can be defined as what produces wealth and welfare while preserving or even regenerating natural capital.

1.3 About this Research

1.3.1 Scope and conceptual framework

The problem of sustainability in manufacturing can be taken at various scales, i.e. product, process and system (Graedel, 2001); and with various perspectives of the triple bottom line (Elkington, 1997), i.e. economic, social and environmental. However, the work excludes certain aspects of sustainability such as social and economic impact, since they are considered as requirements and positive side-effects rather than objectives of the environmental activities illustrated in Figure 1.2. While focusing on the environmental dimension of sustainability, the researcher wished to keep a strong connection to the social and economic dimensions and thus chose to keep the label *sustainable manufacturing* rather than *green manufacturing* or *environmentally conscious manufacturing*. The three main factors in the environmental equation for sustainable manufacturing are (1) resource productivity and waste management, (2) energy as the currency in the conversion of material into products, and (3) efficiency which is limited by the laws of thermodynamics.

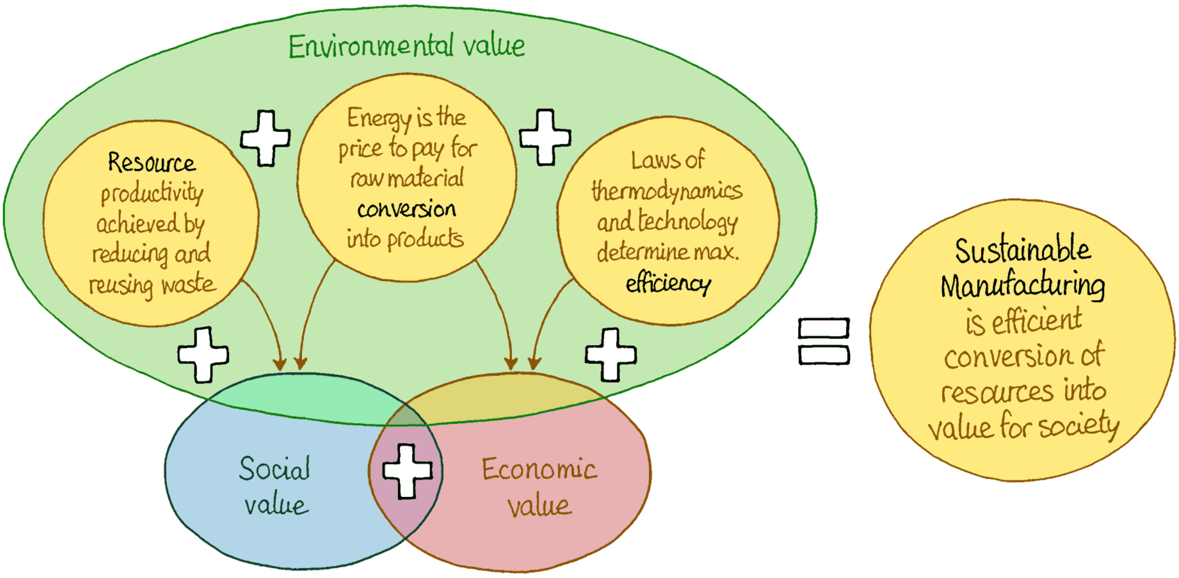


Figure 1.2. Framework for sustainable manufacturing
Adapted from (Elkington, 1997)

The researcher has taken particular interest in the concept of industrial ecology, closely related to the work found under various other labels such as cleaner production (CP), pollution prevention (P2) or sustainable manufacturing. While numerous authors have focused on material life cycle, product supply chain and wider perspectives to allow global improvements to be made, this research focuses on resource productivity in manufacturing and the associated environmental impacts (resource depletion, waste and pollutant emissions), and how this problem can be addressed through practical measures within a factory. It adopts an *ecosystem view* of the factory (gate-to-gate perspective) where all components of the manufacturing system are connected by resource flows, e.g. manufacturing operations, buildings and facilities interacting through material, energy, water and waste (MEW) flows as shown in Figure 1.3.

The term “manufacturing” in this thesis includes direct production and local production management such as plant design, production scheduling, and equipment maintenance. It excludes other functions of the wider enterprise such as product design, supply chain management, workforce organisation, marketing, etc. (Hopp and Spearman, 2008). Thus each component of the factory ecosystem (illustrated in Figure 1.3) can be defined as follow: the manufacturing operations are the direct production processes, i.e. the technology components or manufacturing equipment through which the product goes; the buildings are the architectural components such as rooms, walls, doors, windows, roof, etc.; the facilities (sometimes called utilities) are the components servicing the manufacturing operations and buildings by supplying e.g. compressed air, cooling water, hot water, etc.

1.3.2 Research aim and research questions

This research focuses on resource productivity improvements for sustainable manufacturing using modelling and simulation of MEW process flows through a manufacturing plant. The aim is to generalise sustainable manufacturing practices (SMPs) and guide manufacturers through the process of identifying improvement opportunities within their factory.

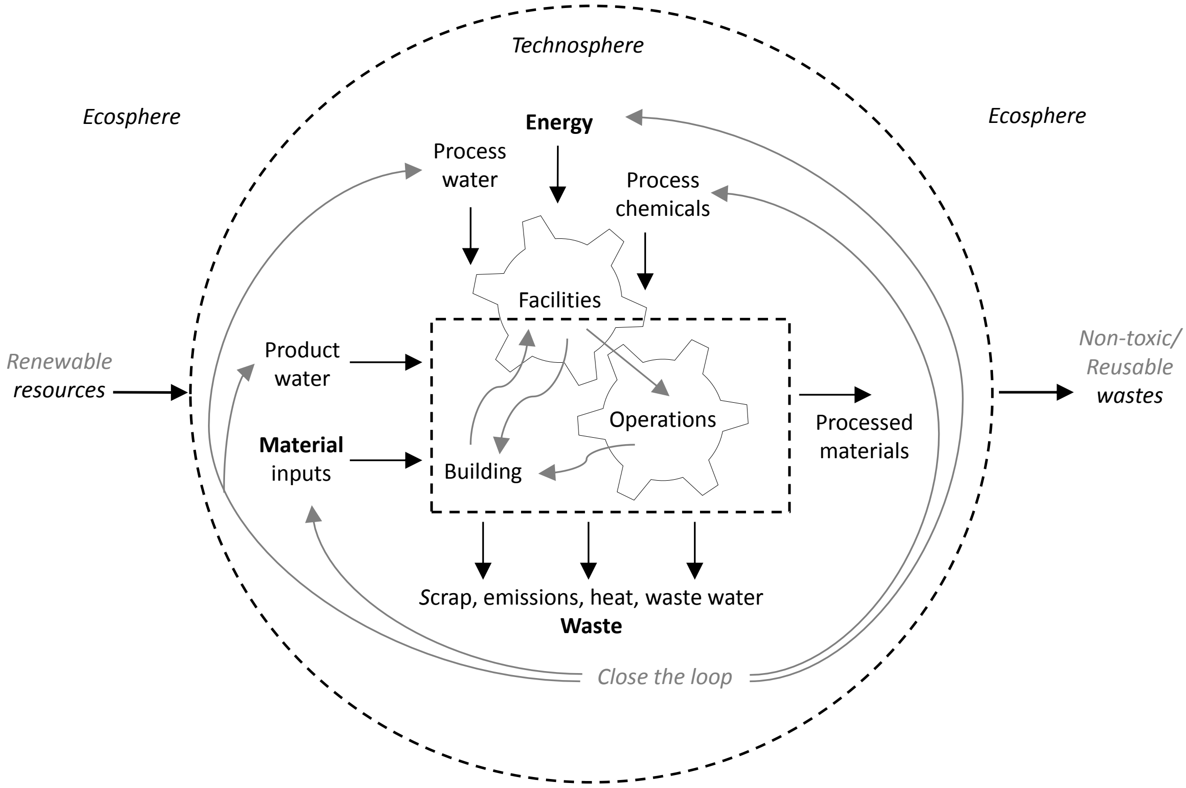


Figure 1.3. Manufacturing ecosystem conceptual model
Adapted from (Despeisse et al., 2012a)

The research started with an early general inquiry about what sustainable manufacturing was in practice in order to compare with scientific knowledge and prescription collected during the literature review. The initial research question was concerned with the *generalisation of practices*. The second question steered the research towards the *identification of inefficiencies and improvement opportunities*. This evolution of the research question resulted from the lack of detailed information on how improvements were identified at the first place and therefore limited the understanding of how practices could be generalised:

1) How to generalise sustainable manufacturing practices across industry?
   (what can/should be done, based on case analysis both in theory and in practice)
2) How to identify improvements in a structured and systematic way?
   (rules/tactics to support generalisation of sustainable manufacturing practices)

1.3.3 Research deliverables and objectives

The research deliverables are a *library of tactics* and its associated *improvement methodology*. The library of tactics defines the rules for taking action on-site based on process data collection and analysis. The improvement methodology supports the generalisation of SMPs by providing a systematic and structured way for identifying improvement opportunities in the resource flows of a factory. The results are directly addressed to manufacturers and the system boundaries of are drawn following the factory fence.

As shown in the thesis structure (Table 1.1), the research objectives are to:

- Explore knowledge in the field of sustainable manufacturing to understand the global challenges and the proposed theoretical solutions (literature review in Chapter 3);
- Explore current strategies and industrial practices to get an overview of what is commonly done in the manufacturing industry (case collection in Chapter 4);

- Formulate generic tactics from the SMPs to provide simple and clear rules to generalise of these practices across industry (tactics design in Chapter 5);
- Develop an improvement hierarchy to guide manufacturers in the journey towards sustainability in a structured and systematic way (tactics prioritisation in Chapter 6);
- Test and refine the tactics and improvement methodology using prototype applications on a selection of industrial processes (tactics testing in Chapter 7).

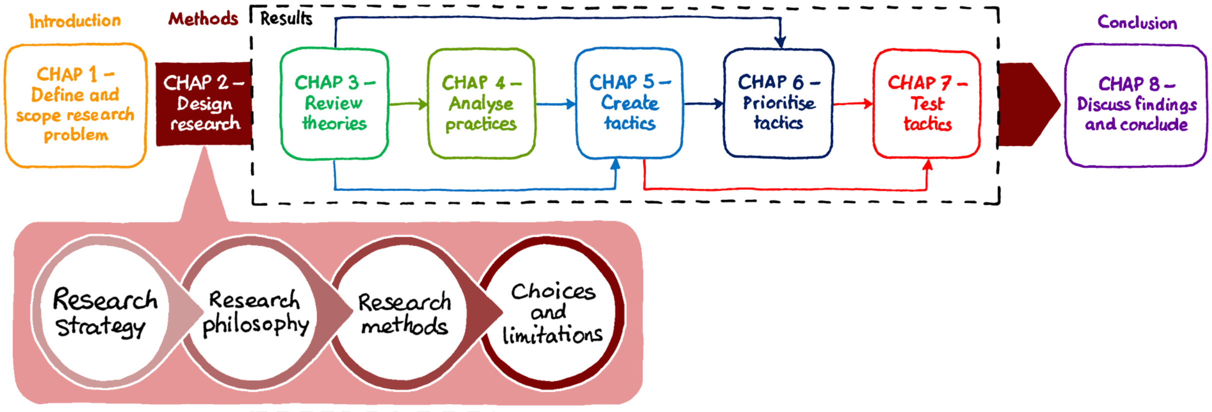
Finally, it is important to note that this research is part of a wider project called THERM (THrough-life Energy and Resource Modelling) and funded by the Technology Strategy Board (project no. TP14/HVM/6/I/BD479L). The project started in October 2009 and finished in September 2012. Part of the work presented in this thesis was conducted collaboratively with the THERM partners: two universities (Cranfield University and De Montfort University), two manufacturing companies (Airbus UK and Toyota Motor Manufacturing UK) and a software developer (IES Ltd). The aim of this project was to develop a modelling and simulation tool—the THERM software— to support sustainable manufacturing plant design and improvement through the integration of sustainable building design and manufacturing process analysis (THERM Project, 2011; Ball et al., 2011).

Table 1.1. Thesis structure and research process

What does the reader want to know?	How did I answer?	Why did I do it?	What does the chapter deliver?
CHAP 1 INTRODUCTION ***What is this research about?***	• Describe the research background, topic, focus and structure	➡ Introduce the research, its context and its significance ➡ Give an overview of the work presented in the thesis	★ Research background and topic: industrial sustainability ★ Research aim and objectives: shift towards sustainable manufacturing ecosystem and generalise good practices ★ Research questions: **1)** How to generalise sustainable manufacturing practices? **2)** How to identify sustainable manufacturing improvements? ★ Thesis structure
CHAP 2 RESEARCH DESIGN ***How was the research done?***	• Describe the process and the approaches used to conduct research	➡ Show scientific rigour and understanding of research philosophy and design options	★ Research process overview: purpose, strategy and methods ★ Research philosophy: post-positivism ★ Research methods: case analysis, theory building and testing
CHAP 3 LITERATURE REVIEW ***What is already known?***	• Explore knowledge in sustainable manufacturing and other related fields of research	➡ Understand the challenges and existing theoretical solutions in the area	★ Gaps in knowledge: manufacturing ecosystem perspective, generalisability of sustainable manufacturing practices ★ Validation of research question and objectives
CHAP 4 CASE COLLECTION ***What is already being done?***	• Explore typical strategies and practices in the manufacturing industry	➡ Understand the mechanism for identifying improvement opportunities	★ Sustainable manufacturing practice database ★ Initial theory building from case collection findings : tactics for generalisation of sustainable manufacturing practices
CHAP 5 TACTICS LIBRARY ***How can sustainable manufacturing practices be generalise d?***	• Translate the sustainable practices into generic tactics by capturing the mechanisms of change	➡ Provide clear and simple rules to generalise of sustainable practices across industry	★ Structured library of 20 tactics covering 200+ practices ★ Refined theory: from tactics formulation to tactics access
CHAP 6 IMPROVEMENT HIERARCHY ***How can the tactics be accessed and used?***	• Create a methodology to model manufacturing systems and to identify/prioritise improvements	➡ Guide the user through the steps of data collection, model creation and tactics implementation	★ Improvement methodology to access tactics through manufacturing system modelling ★ Refined theory: from tactics access to tactics prioritisation
CHAP 7 IMPROVEMENT METHODOLOGY ***How does is work and is it working?***	• Test and refine the improvement methodology to access tactics using a factory modelling approach	➡ Validate the improvement methodology and demonstrate how tactics can be used through modelling	★ Fast Prototype applications ★ Testing and validation of theory: tactics as a support for the creation of sustainable manufacturing ecosystem
CHAP 8 DISCUSSIONS & CONCLUSION ***What are the findings?*** ***What are the implications?*** ***What are the next steps?***	• Reflect and interpret the research findings in the light of a wider context • Compare with other theories • State strengths and weaknesses Synthesise findings , their significance and implications • Suggest further work	➡ Show that the findings answer the research question and fulfilled research objectives ➡ Show how the work fits with existing work and contributes to knowledge	★ Synthesis of research findings ★ Contribution to theory: tactics to generalise sustainable practices & shift towards sustainable manufacturing ecosystem ★ Contribution to practice: improvement methodology to guide manufacturers through the identification of inefficiencies and prioritise improvement options ★ Research limitations ★ Recommendations for future research

Chapter 2 RESEARCH DESIGN

This chapter explains how the research was carried out and motivates the research methods used. The first section describes the research strategy to give an overview of the research process and its logic. In the second section, the underlying philosophical considerations and the choices made for this research are discussed. Then the research methods, the procedure for case collection and analysis, theory building, and the context for prototype applications with industrial partners are described. Finally, the limitations of the selected research design are discussed in light of the purpose of this research.



2.1 Research Strategy

Knowledge creation must follow a rigorous research process. The research strategy describes the logic of inquiry by providing a set of procedures for addressing research questions (Blaikie, 2000). This section presents the research strategy to give an overview of the process used in this research as illustrated by Figure 2.1. The relationship between the strategy and philosophy are discussed later in this chapter.

The starting point is a preliminary study of the topic to understand the current state of knowledge and clearly define the research problem before formulating the aim, objectives and research questions (see Chapter 1 Introduction). The topic of this research is sustainable manufacturing and the boundaries of the system studied limited to factory gates. The preliminary study of the topic revealed that this field of research embraces numerous disciplines and there is no definite theory or model for what sustainability is for the manufacturing industry. Therefore, a conceptual manufacturing ecosystem model (Despeisse et al., 2012a) was adopted to give the direction of change needed for sustainable manufacturing at factory level (see Figure 1.3). Moreover, there are no tools for analysing and modelling resource flows in a manufacturing (eco)system, and for identifying and prioritising improvement opportunities.

The aim of this research is to generalise sustainable manufacturing practices (SMPs) by developing rules (generic tactics) and an improvement methodology for modelling manufacturing systems and identifying improvement opportunities in a systematic and structured way. To do so, the work focuses on resource productivity improvements using modelling and simulation of MEW process flows through a manufacturing plant. The work is directly addressed to manufacturers to help improve the MEW flows in their factory and therefore has practical implications through the modelling tool developed as part of a wider project (THERM Project, 2011).

The two research questions can be distinguished as the first one being about the *substance*, i.e. what are the rules of sustainable manufacturing, and the second being about the *process*, i.e. how to identify improvement opportunities (Bickman, 1987):

1) How to generalise sustainable manufacturing practices across industry?
   (what can/should be done, based on case analysis both in theory and in practice)
2) How to identify improvements in a structured and systematic way?
   (rules/tactics to support generalisation of sustainable manufacturing practices)

The methods used for theory building were cross-sectional case analysis from secondary data source and conceptual clustering for identifying patterns from which practice generalisation rules could be extracted. The data collection started with a general inquiry about what sustainable manufacturing was in practice in order to compare with scientific knowledge and theoretical solutions reviewed during the literature review.

Figure 2.1 shows the cyclic process followed in this research: it goes through three main phases (exploration, explanation, testing) twice. Therefore, it combines multiple approaches and methods to explore existing knowledge and to both building and test theory. While the figure shows neatly separated phases which are used to structure this thesis into chapters, the chronology of the work actually overlapped the methods.

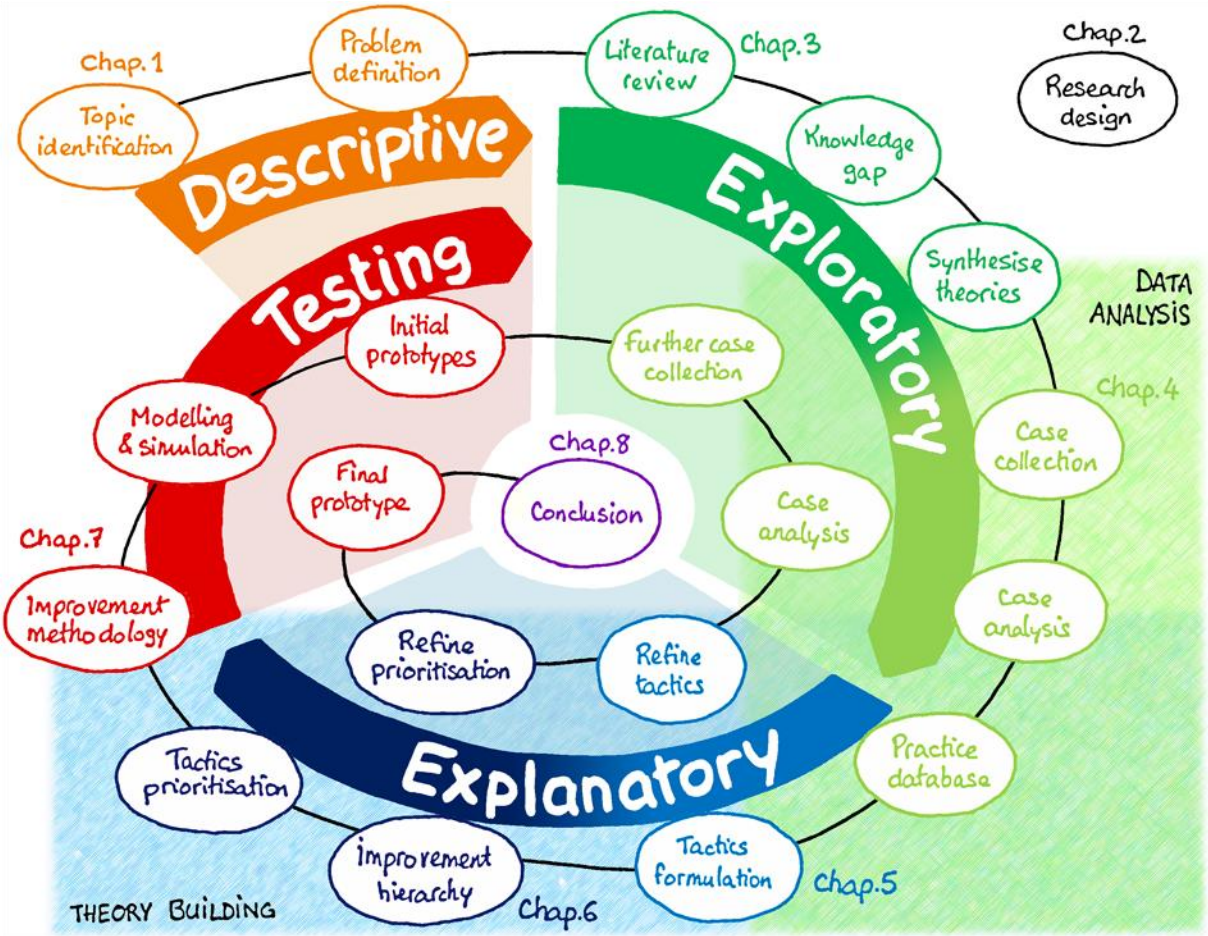


Figure 2.1. Overview of the research process steps and phases

To address the first research question, the data collection started during the *exploratory phase* to investigate the knowledge in the area of sustainable manufacturing. In addition to peer-reviewed literature, various sources were used for this exploratory analysis, including corporate websites and trade publications. Both theory and practice were analysed to understand the current trends and the extent of the work already accomplished both in academic research and in industry. The approach was *qualitative* to capture a landscape of activities being done in industry. The data collection and analysis must cover a sufficiently wide range of practices to gain understanding of the type of activities done and identify mechanisms and patterns. Therefore, the researcher chose to use *cross-sectional design* as it allows capturing a landscape of activities being done in industry and it uses on a selection of criteria for analysing all cases in a consistent way. The rationale for selecting *multiple-case* design was based on the hypothesis that there are a certain (limited) number of different mechanisms for SMP and the researcher aimed at collecting sub-groups of cases covering each type of practice.

The second research question was later formulated from the first observation of data collected: there is a lack of detailed information on how to identify inefficiencies and improvement options, and therefore limited the understanding of how practices could be generalised to answer the first research question. To address the second research question, the research further extended to an *explanatory phase* for *theory building* to explain the causes and mechanisms of changes towards sustainable manufacturing. Generic tactics are formulated to capture how SMPs work and how other companies can replicate these SMPs in their own factory by removing the context-specific aspects and extracting the mechanism of change. Once the tactics are created, they need to be implemented via an improvement methodology to guide the user through the different steps from collecting data about the manufacturing system being studied, model creation and simulation, through to identification and prioritisation of improvement options.

Finally, the third phase of this research consists of *testing* to refine and validate the theory using prototype applications which are part of the THERM project.

2.2 Research Philosophy

This research uses a combination of inductive and deductive reasoning. This strategy has underlying ontological and epistemological assumptions. This section compares different philosophical perspectives and highlights the ones selected for this study.

The choices in designing one’s research must account for the nature of reality (ontology) and the ways knowledge about this reality is acquired (epistemology). Epistemology does not only define how reality can be observed and understood, but also how it can be affected, i.e. how our actions can change the world. The combination of ontology and epistemology constitutes a research paradigm (Bryman and Bell, 2007; 2003).

Regarding the nature of reality, there are two main competing ontological considerations: idealism and realism. On the one hand, idealism assumes that reality consists of representations created by human mind. There can be multiple realities (or perspectives) of the external world as it is made up of interpretations shared by people. In social research, constructionism, which is close to idealism, is a dominant ontology in business research. It assumes that “social phenomena and their meanings are continually being accomplished by social actors” (Bryman and Bell, 2007; 2003). In other words, reality is socially constructed and different people will give different meanings according to their own version of reality.

On the other hand, realism assumes that there is an objective world independent of the observer. Realists believe that the purpose of philosophy and science is to locate externally true meanings and that new observations bring us closer to understanding reality. There are variations in the realist ontologies with differences in the way reality can be accessed (Blaikie, 2000) which are mapped in Figure 2.2. They are intermediate ontologies between the two major forms of realism: empirical realism and critical realism (Bryman and Bell, 2007; 2003) which correspond to the right-hand side of Figure 2.2, bottom and centre respectively. This research follows the subtle realist ontology which accepts the existence of an external and independent reality but also recognises the potential biases in the observer's interpretation of reality (Blaikie, 2000).

Finally, dualism (or Cartesian dualism) makes a distinction between the physical world and the observer's mind. This ontology combines the realist view that reality is independent of the observer and the idealist view that truth in a representation of reality in the human mind (Van de Ven, Andrew H., 2007).

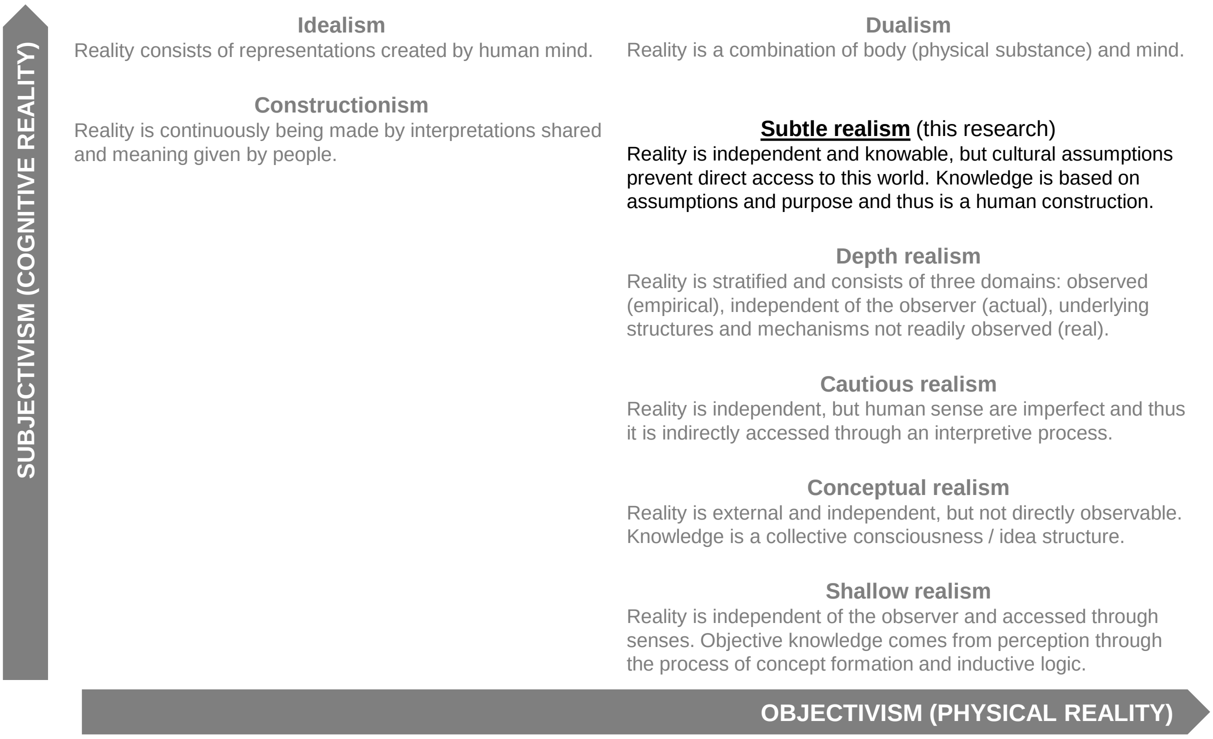


Figure 2.2. Ontological considerations
Adapted from (Blaikie, 2000; Bryman and Bell, 2007; 2003)

Associated with the competing idealist and realist ontologies, the extreme epistemological assumptions are rationalism and empiricism. In the domain of social research, interpretivism is often presented as the contrasting epistemology to positivism (Bryman and Bell, 2007; 2003). In rationalism and interpretivism, knowledge and meaning are represented by human thoughts as suggested by the idealist ontology. They are socially constructed through shared experiences and interactions rather than discovered from the world. There can be different realities (or perspectives) depending on the observer because different meanings and interpretations can be derived from a single phenomenon.

Conversely for empiricists and positivists, the observer is neutral and in direct, undistorted contact with reality. Thus knowledge is an objective and accurate representation of the external world under the realist ontological assumption that there exists an external and independent reality (or absolute truth). Positivism assumes that knowledge is derived from data received through sensory experience and from logical and mathematical analysis of such data. Empiricism adopts a narrower view on the method to gain knowledge: it assumes that knowledge can only be gained through sensory experience.

As for research ontology, there are other epistemological considerations with intermediate versions as shown in Figure 2.3. For instance, pragmatism reconciles rationalism and empiricism “by showing that knowing and doing are indivisible part of the same process” (Van de Ven, Andrew H., 2007). It accepts the existence of a mind-independent physical world but does not aim at finding the truth or understanding reality. Instead pragmatic ideas and theories are developed to provide useful models of reality and tools to support human problem solving.

Figure 2.3 maps the epistemologies as function of the process of knowledge creation which can originate from human senses (observation and experience) or from human thought (mental construction). This distinction is closely linked to ontological considerations as sensory experiences suggest the existence of an external world. But it is important to note that this distinction does not necessarily correspond to the subjective-objective dichotomy in the nature of knowledge. For instance, rationalism assumes that knowledge and meaning are products of human mind through a purely mental process, but it also recognises that they can be objective and validated through deductive reasoning. Conversely post-positivism, which is the paradigm chosen for this research, relies on sensory experience to gain knowledge but also recognises potential bias in judgement and thus a certain degree of subjectivity.

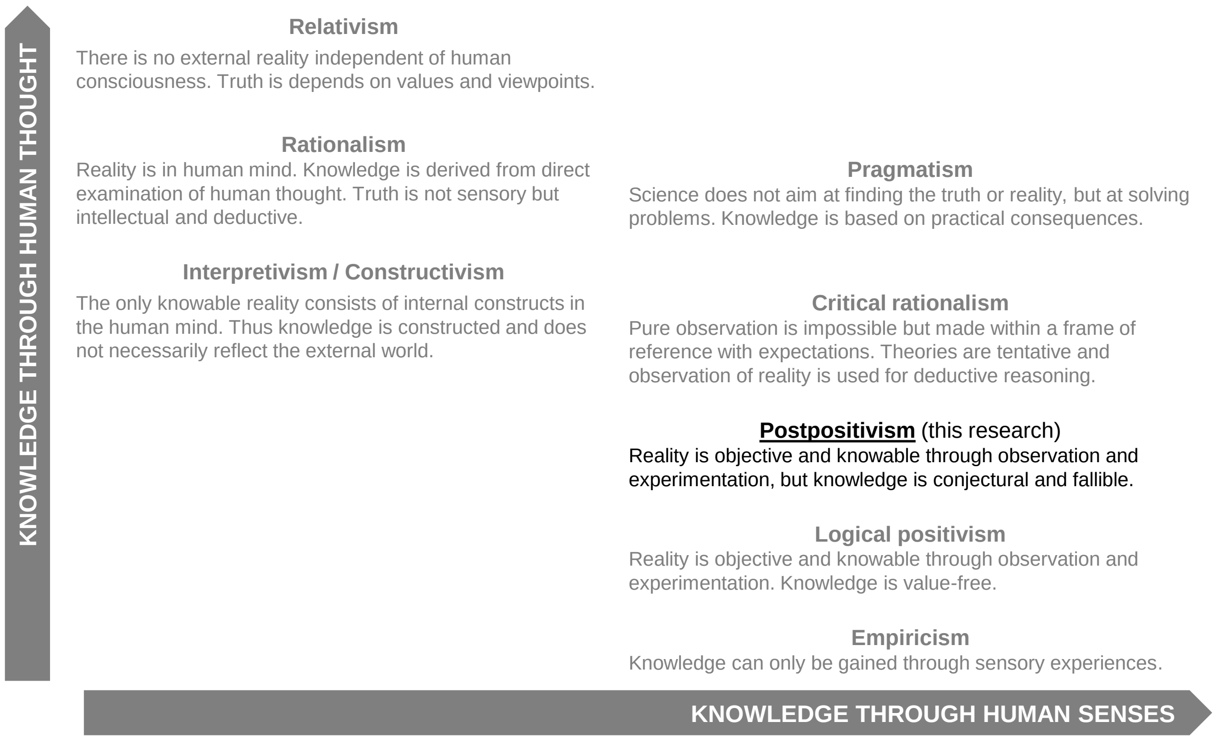


Figure 2.3. Epistemological considerations and research paradigms
Adapted from (Blaikie, 2000; Bryman and Bell, 2007; 2003)

2.3 Research Methods

2.3.1 Case collection

During the first phase of the research (exploratory), the research question addressed was: How to generalise SMPs across industry? To answer this question, the researcher chose an empirical cross-sectional analysis of industrial cases from secondary sources (Chapter 4) as the research method. With this empirical inquiry method, contemporary phenomena in real-life context are investigated and theory is built from observations. The method selected was multiple-case analysis as it allows capturing a landscape of activities being done in industry. The rationale for selecting multiple-case design was based on the hypothesis that there are a certain (limited) number of different mechanisms for SMP and the researcher aimed at collecting sub-groups of cases covering each type of practice. Categorisation methods were then used to create the initial theory.

Case collection from secondary sources (peer reviewed and non-peer-reviewed studies) was chosen over surveys, interviews or experimentations because the researcher was aiming at capturing a landscape of SMPs as wide as possible within the first year of the research. The case study conducted was indirect as it used secondary sources: the research was based on reported cases in scientific literature and trade website rather than on direct observation of SMPs in the industry. Cases were collected from various sources dedicated to the topic of manufacturing operation improvements for environmental sustainability. Given the exploratory nature of the work, sources included not only academic publications, such as books and journal articles, but also trade literature, such as organisational and corporate websites. This method enabled the researcher and the THERM project team[1] to collect and analyse a total of 1000 SMPs from 200 sources within the first two years of the research.

Experimentation was not selected for this research although it could be used to identify the best procedure for improvement implementation under various conditions or with various influencing factors. Experimentation however is recommended as part of further research to test improvements' implementation procedure (improvement methodology developed in Chapter 7). Survey and interview methods could have provided more in-depth case studies by questioning and interviewing energy managers, waste managers, water experts, maintenance teams, production teams, facility engineers, process engineers, etc. these alternative methods could be used to better understand the motivations, challenges and procedures for sustainable manufacturing improvement activities. But again, they were not selected for this research: the researcher selected case collection from secondary sources because this technique has the potential to quickly provide a larger number of cases (time-efficient).

The objective of this research was to capture a wide landscape of SMPs in order to identify patterns. The analysis followed an inductive-deductive reasoning cycle to build theory from observed patterns using conceptual clustering and to refine theory by checking completeness of the findings using a simplified representation of manufacturing systems. The analysis was qualitative as the case collection was aiming at understanding the breadth of practices to allow theory building through a broad *analytic generalisation* rather than getting a representative sample of practices to allow a *statistical generalisation* (Yin, 2009, 1994).

2.3.2 Tactics development

The purpose of the second phase (explanatory) was to develop the library of tactics and improvement methodology for more sustainable manufacturing operations. This phase involved the formulation and generalisation of theories to answer both research questions: how to generalise good practices and how to identify improvements in a structured and systematic way. First the tactics were developed to bridge the gaps both in knowledge of what should be done (theory) and in practice how to do it in the factory (Chapter 4). The research process to obtain the library of tactics is illustrated in Figure 2.4. Then the improvement methodology was developed to provide guidelines and clear procedures for implementing

[1] More details about the data collection and external support to populate the SMP database will be discussed in Chapter 4 (4.2Sourcing, Selecting and Interpreting Case Study Reports).

tactics via modelling of manufacturing systems (Chapter 7). The methods for developing the improvement methodology are described in the next section (2.3.3 Tactics prioritisation).

While the case study was an empirical method to build initial theory, non-empirical concept development was used to further revise the theory and to finalise the tactics library. The theory emerged from the data by observing and interpreting patterns, similarities and differences in the practices in the light of theoretical principles collected in scientific literature (from the literature review in Chapter 3) and of graphical data display using Despeisse et al. and Oates et al. factory modelling approach (Despeisse et al., 2012a; Oates et al., 2011b).

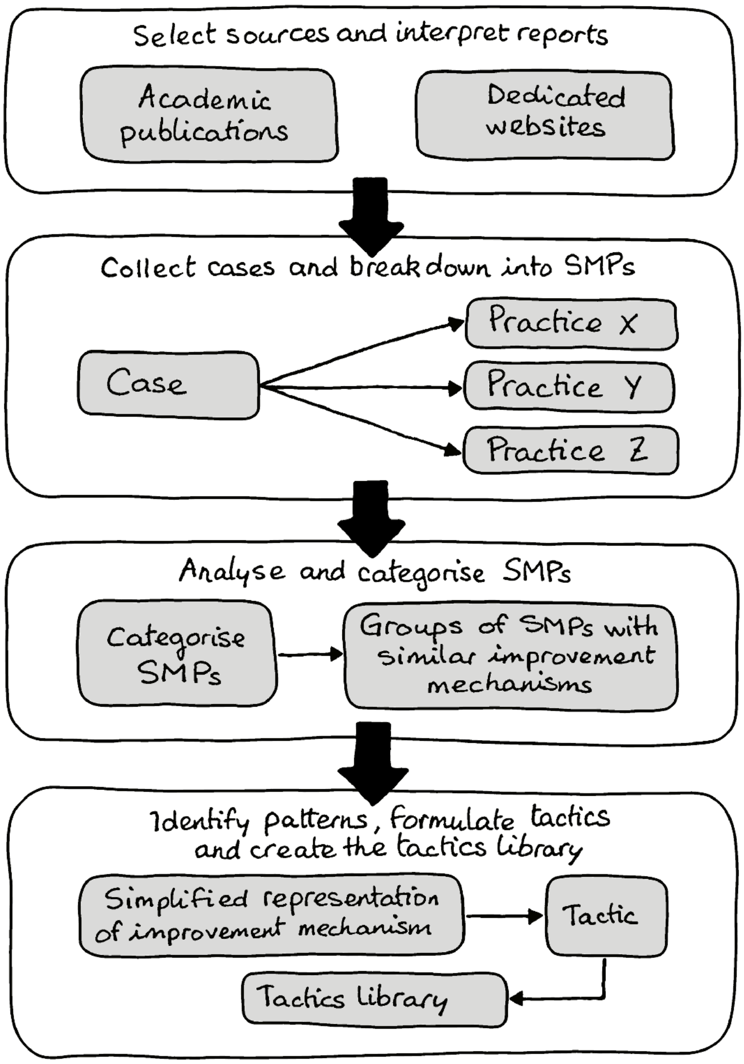


Figure 2.4. Cross-sectional case analysis and tactics library development

Two methods of logic reasoning were used as the work progressed through multiple induction-deduction cycles. The initial theory was developed following an inductive reasoning. Inductive reasoning moves “from specific observations to broader generalizations and theories. […] In inductive reasoning, we begin with specific observations and measures, begin to detect patterns and regularities, formulate some tentative hypotheses that we can explore, and finally end up developing some general conclusions or theories.” (Trochim, 2006) Tactics were formulated from practices using an inductive approach and the library of tactics was checked for completeness using a deductive approach.

Each case collected from the literature was divided into individual practices defined as an action or set of actions improving the manufacturing system’s environmental performance.

The elements of interest for this analysis were the mechanisms of improvement rather than the technology used or the reported benefits. Therefore, the analysis adopted a simplified representation of manufacturing systems (graphical data display) to better understand how the improvements resulted in the system's reconfiguration. These reconfigurations were considered as the mechanisms of improvement to identify patterns in the types of improvement achieved. Practices were classified based on these patterns using conceptual clustering. (Fisher, 1987) defines conceptual clustering as "a type of learning by observation (as opposed to learning from examples) and is an important way of summarizing data in an understandable manner."

The structure of the practice database considered the following:

- How cases fit in the database: understand what was done based on reported data, break down cases into practices (unit of analysis) and categorise individual practices;
- How the database is accessed: associate practices with "labels" and keywords;
- How the data can be used: find out about existing technological solutions, target specific benefits, identify specific inefficiencies, or adjust specific process parameters.

Finally, each group of practices was synthesised into a generic tactic In other words, the tactics allowed the rules of operational improvements for sustainable manufacturing to be coded and captured the (context-free) mechanisms of SMPs to allow generalisation.

After the previously described inductive process, a second round of case collection and analysis was conducted to further populate the practices database. This time, deductive reasoning was used to work from more generic (tactics and "labels") down to observation of more specific data. Ultimately it enabled the researcher to test the theories with specific data and to refine and confirm the original theories.

2.3.3 Tactics prioritisation and implementation

The development of the improvement hierarchy and methodology was also part of the explanatory phase of the research and addresses the second research question: how to identify sustainable manufacturing improvements in a structured and systematic way. The purpose of the improvement methodology is to provide a clear procedure and guidelines to identify operational improvements for sustainable manufacturing. The improvement hierarchy allowed prioritising the tactics to ease their selection during this iterative process of identifying operational improvements. The research process to develop the improvement hierarchy and methodology is illustrated in Figure 2.5.

First an improvement hierarchy was derived from a synthesis of literature review findings. It includes various sets of strategies, principles, options and hierarchies developed by different groups of researchers. These various sets are highly compatible although they were conceived with different perspectives and with different purposes. By bringing them together and synthesising them, a more complete and coherent set of strategies was gathered and prioritised.

The researcher used a thematic analysis method (Bryman and Bell, 2007; 2003) to gather and summarise the main themes in the literature on sustainability in general and industrial sustainability in particular. This method was developed to conduct systematic reviews in medicine and health research (Dixon-Woods et al., 2005; Thomas and Harden, 2008) but has also been used in other fields of research such as supply chain management (Wu, 2008) and information technology (Cruzes and Dyb, 2011).

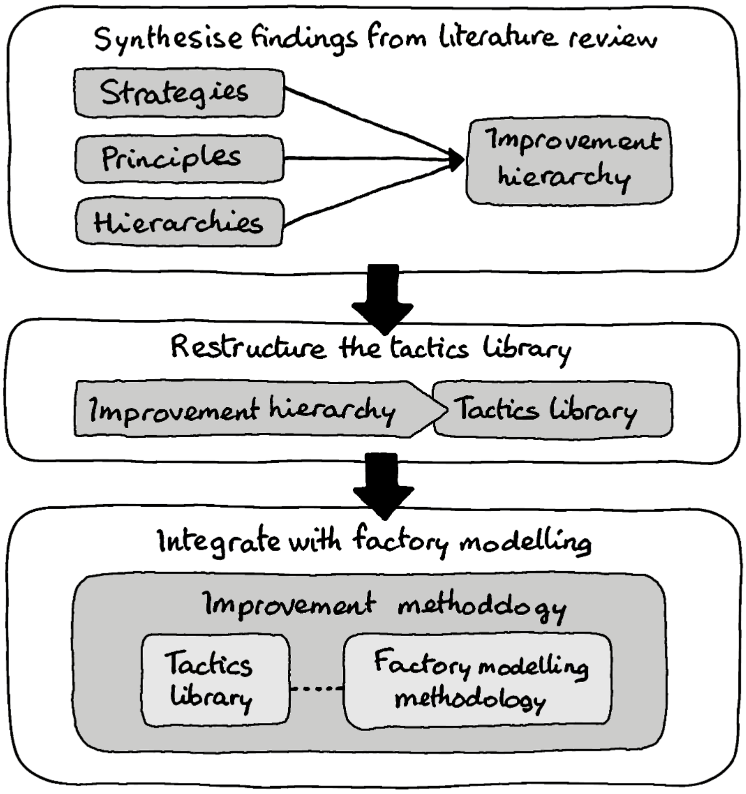


Figure 2.5. Literature synthesis and improvement methodology development

To develop the improvement hierarchy, the various sets of strategies and principles were listed to allow the identification of important and recurrent themes. This process was an inductive one as the researcher interpreted and translated the strategies and principles to obtain a common language, perspective and understanding for all levels of the improvement hierarchy.

The tactics library was then restructured according to the improvement hierarchy to ease their use and implementation. The tactics can help manufacturers to translate sustainability concepts into tangible actions while the improvement hierarchy can support decision-making as prioritisation is needed to select appropriate improvements. The restructured library of tactics is then combined with a modelling methodology (Despeisse et al., 2012b) to create an *improvement methodology* which is used to test, refine and validate the tactics library. In other words, the improvement methodology guides manufacturers step-by-step through the modelling and analysis of their factory (or processes) to identify improvements towards more sustainable manufacturing operations.

2.3.4 Testing and validation

Keeping in mind that this research is part of a larger project developing a modelling and simulation tool (THERM Project, 2011; Ball et al., 2011), the testing phase of this research was conducted through a collaborative work with the THERM partners. Although four prototype applications were conducted as part of the THERM project, only two of the prototype applications are reported in this thesis as they are the most relevant for testing the tactics and the improvement methodology.

The prototype applications aimed at testing various aspects of the modelling and the access to tactics. The initial prototypes were used to test certain aspects of the factory modelling approach and check tactics could be accessed through the process data used to create the factory model. The final prototype application was used to test and refine the improvement methodology which embeds the elements of the tactics library into a practical application framework; in the case of the THERM software, this takes the form of a *Navigator* (Quincey and McLean, 2011). It is a step-by-step approach based on factory modelling integrating the structured library of tactics to improve the resource flow by viewing the factory as an ecosystem. A factory modelling prototype tool integrating buildings, facilities and manufacturing operations is presented to test the improvement methodology (Chapter 7).

The integration of tactics was achieved by coding them into the THERM tool and consequently by integrating the principles of sustainable manufacturing improvement into the modelling and simulation tool analysis. In turn this tool aims at helping manufacturers to identify improvement opportunities in their resource flow using factory modelling and the library of tactics following the improvement methodology.

2.4 Limitations of the Selected Methods

The tactics development was based on a cross-sectional case analysis of sustainable manufacturing practices. The researcher recognises the limitations of the research methods chosen. This section discusses these limitations and contingent measures taken by the researcher to increase the quality and validity of the research design based on the four critical conditions of design quality: construct validity, internal validity, external validity and reliability (Yin, 2009).

The first limitation of the case analysis is the lack of control on the data source (unlike in experimentation) when observing a phenomenon and its variables in real-life context. There is a potential bias in reported cases, particularly when cases are coming from different sources. This bias in the data collection must be acknowledged and described when the conditions of observation and reporting are influential (e.g. source is a publication or a website focused on specific aspects such as waste management, water conservation, energy efficiency, etc.). This relates to the first critical condition of design quality: construct validity is challenging for case study research as "subjective judgements are used to collect data" (Yin, 2009, 1994).

Internal validity which is mainly a concern for explanatory analysis (Yin, 2009) must be addressed by carefully selecting the analytic techniques for identifying patterns in the data. For instance, pattern-matching technique compares empirical patterns with predicted ones (Trochim, 2006). If the patterns coincide, the results strengthen the internal validity of the study.

Regarding external validity, there may be concerns about case studies as a basis for scientific generalisation as the case collection might not be a good representation of the whole population and therefore limits the relevance for a given sample. This issue can be addressed by using replication logic in the multiple-case study (Eisenhardt, 1989). Replication logic enables the analytical generalisation of the results to other cases outside the study by developing theories explaining the recurrent patterns or regularities observed (Blaikie, 2000).

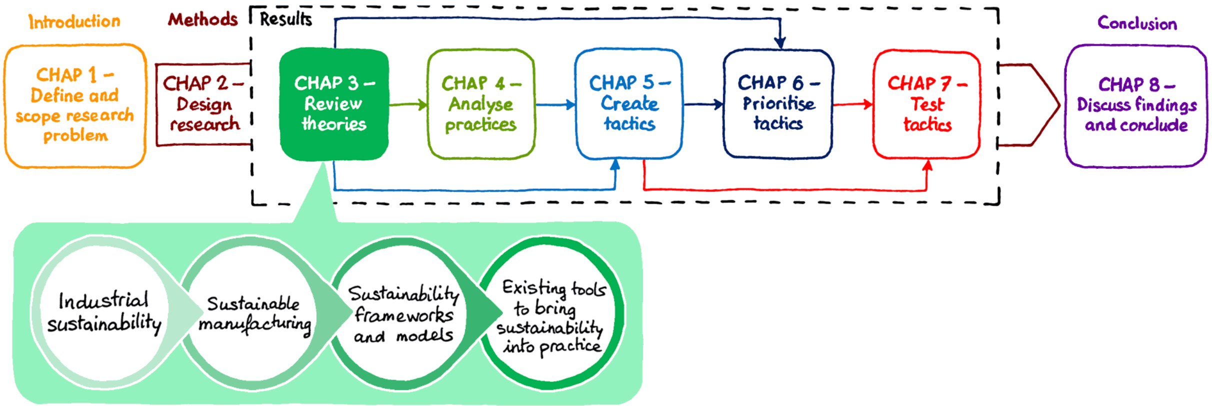
2.5 Chapter Summary

The aim of this research is to generalise SMPs by creating a library of tactics and an improvement methodology to guide manufacturers in identifying improvement opportunities. The work is directly addressed to manufacturers to help improve their resource flows in the factory and therefore has practical implications through the modelling tool developed as part of a wider project (THERM Project, 2011). The research process is composed of three main phases: exploration with literature review (Chapter 3) and case analysis (Chapter 4), explanation with the development of the tactics library (Chapter 5), the improvement hierarchy (Chapter 6) and the improvement methodology (Chapter 7), and finally testing (sections 7.4 and 7.5). The first research question focuses on the generalisation of SMPs and the second question focuses on the mechanisms for identifying improvements to further support the generalisation of SMPs. The methods used for theory building were cross-sectional case analysis and conceptual clustering for identifying patterns and formulating tactics library. Finally, the research findings are tested and validated through prototype applications which are part of the THERM project.

Chapter 3 SUSTAINABLE MANUFACTURING THEORY

Part of this chapter has been published in **Despeisse, M., Ball, P. D., Evans, S. and Levers, A. (2012), "Industrial ecology at factory level – a conceptual model",** ***J. of Cleaner Production*** **31(3-4), pp. 30-39** of which the thesis author was the main contributor.

This chapter is a review of scientific literature on industrial sustainability and other relevant topics of interest for this research. The first section gives an historical review of the literature in industrial sustainability in general, and sustainable manufacturing in particular. The second and third sections focus on sustainability as a concept and on various approaches and supporting tools available to help the manufacturing industry in its journey towards sustainability.



3.1 Manufacturing and Sustainability: a Historical Review

3.1.1 Sustainability in industry

The Environmental Movement is commonly accepted to have started in the 1970s with the Earth Day demonstrations. This event emerged from the spread of public awareness about environmental issues such as air and water pollution; waste disposal, resources scarcity, nuclear radiation, pesticide poisoning and accumulation in the environment. However, the story of societal sustainability in general, e.g. Malthus essay on population growth (Malthus, 1798; Marsh, 1864), and industrial sustainability in particular begins far before this (Sidgwick, 1883). The Progressive Era was a movement of social activism and political reform in the United States which started in the late-1800s followed by the creation of association and other movements (Pezzoli, 1997).

The need for achieving sustainability in industry is now a well-recognised due to arising environmental problems (Kemp, 1994; Batterham, 2003). Such problems are recognised to be largely caused by industrial activities: depletion of non-renewable resources and environmental pollution. The motivation for companies to take action is no longer purely economic; the incentives are coming from many directions: stricter environmental and social regulations, consumer awareness and societal demand for environmentally and socially responsible products (Ball, 2010). Especially for manufacturing companies which are the central players in industrial systems, sustainability is a question of survival (Igartua et al., 2010) as their role is to sustainably generate and preserve high living standard worldwide through the production of goods and services so that the next generations will be able to enjoy the same standard of living as well (Jackson, 2005; Evans et al., 2009).

Why should industry care about sustainability? In the past two decades, there has been an increased interest in the sustainability performance of companies. Concepts of corporate citizenship, corporate social responsibility and environmental management (Matten and Crane, 2005; Hibbitt and Kamp-Roelands, 2002) have quickly gained popularity as stakeholders are asking for more environmentally responsible business practice (Hart, 1995). With the increased demand for greener products and services (Daily and Huang, 2001), becoming more sustainable attracts new customers. There is also a pull from market place, reputation of the business and gain market shares. Companies want to be the first-mover, maintain market leadership, do better than the competition (Kleindorfer et al., 2005). And finally, there is a push from governments with stricter regulation, higher penalties for non-compliance and tax benefits from doing the "right thing" (Hibbitt and Kamp-Roelands, 2002). More sustainable practice is simply good business practice (Reinhardt, 1999): it also reduces risk, and reduce exposure to resource scarcity (materials, energy and transport).

In summary, improving the company's environmental performance can result in long-term cost reduction, fulfilment of regulatory requirements, more attractive products and services, better ethical practice, natural resource preservation, improved public image and as a consequence enhanced competitive advantage.

3.1.2 Sustainable manufacturing

The environmental burden linked to human activities has become an important global issue and a great challenge for our society popularised by many authors (Carson, 1962; World Commission on Environment and Development, 1987; Holdren and Ehrlich, 1974; Meadows and Club of Rome, 1974). Manufacturing companies are increasingly engaged in environmental activities and can even benefit from making sustainable changes in the way they operate (Del Brío and Junquera, 2003; Rusinko, 2007; Menzel et al., 2010). The two main technical improvement approaches identified are technological change and process management (Gupta and Cawthon, 1996; Raymond et al., 1996). An illustration of both the economic and environmental benefits of sustainable manufacturing is apparent in the cost savings due to energy reduction and waste minimisation.

In the sustainability context of this research, 'manufacturing' is defined as the transformation process of resource inputs into useful outputs through the use of technology with limits on efficiency due to the laws of thermodynamics (Gutowski et al., 2009). This idea captured by the principle of *energy intensity* (Smil, 2003) which considers energy as the price to pay for resource conversion. Although the energy intensity has decreased with technological advances and efficiency improvements in manufacturing, the total amount of energy as well as the associated environmental impact have dramatically increased during the human advances of the twentieth century (Smil, 2003). In other words, manufacturing is responsible for the efficiency with which raw materials are converted into products and services through the use of energy, but it also is responsible for the resulting waste and pollution generated during this conversion. Therefore, manufacturing has traditionally been associated with undesirable environmental side effects such as increased pollution although efficiency is improving; this is the so-called rebound effect (Cleveland and Ruth, 1998).

While there is no universal definition for sustainable manufacturing, it is generally accepted as a new paradigm for developing socially- and environmentally-sound techniques to transform resources (material, energy, water) into economically-valuable products and services. Since late 1980s, many concepts, such as pollution prevention (P2) (Davis and Costa, 1995) and industrial ecology (IE) (Ayres, 1989), have been developed in response to the increasing pressures from stakeholders and ever more stringent regulations to improve their environmental performance. Frosch and Gallopoulos were the first authors to clearly introduce sustainability into manufacturing strategies and they established a ground for research in sustainable manufacturing with the concept of *industrial ecosystem* (Frosch and Gallopoulos, 1989). Early work in the field of sustainable manufacturing was mainly done under these topics and only recently became a field of research on its own under various labels such as *environmentally conscious* (or *benign* or *responsible*) *manufacturing*, *green manufacturing*, *cleaner production*, *sustainable production*, etc. A list of definitions for these terms can be found in Table 3.1.

For the purpose of this research, sustainable manufacturing is defined as efficient and effective conversion of resources into value for society while respecting Earth's carrying capacity. The three main considerations for resource conversion efficiency are: (1) resource productivity and waste management, (2) energy as the currency in the conversion of material into products, and (3) efficiency which is limited by the laws of thermodynamics.

Table 3.1. Definitions of Sustainable Manufacturing (or other labels) in the literature

Reference	**Definition**
(Allwood, 2005) Sustainable manufacturing	"Developing technologies to transform materials without emission of greenhouse gases, use of non-renewable or toxic materials or generation of waste."
(Frosch and Gallopoulos, 1989) Industrial ecosystem	"In such a system [industrial ecosystem] the consumption of energy and materials is optimized, waste generation is minimized and the effluents of one process whether they are spent catalysts from petroleum refining, fly and bottom ash from electric-power generation or discarded plastic containers from consumer products serve as the raw material for another process."
(Glavič and Lukman, 2007) Sustainable Production	"Sustainable production is creating goods by using processes and systems that are non-polluting, that conserve energy and natural resources in economically viable, safe and healthy ways for employees, communities, and consumers and which are socially and creatively rewarding for all stakeholders for the short- and long-term future"
(Hibbard, 2009) Sustainable manufacturing	"Design products that conserve energy, reduce waste and eliminate pollution - in a sustainable way."
(Melnyk and Smith, 1996) Green manufacturing	"A system that integrates product and process design issues with issues of manufacturing planning and control in such a manner as to identify, quantify, assess, and manage the flow of environmental waste with the goal of reducing and ultimately minimizing environmental impact while also trying to maximize resource efficiency."
(Mohanty and Deshmukh, 1998) Green productivity	"Green productivity signifies the search for value-adding technologies that can resolve the issue of generation of higher output with minimum consumption and maximum conservation of inputs, yet enabling the balance between the economy and the physical environment."
OECD definition of sustainable production in 'Eco-Innovation in Industry'	"The creation of goods and services using processes and systems that reduce the use of natural resources and toxic materials and emissions of waste and pollutants, protect workers, communities and consumers, and are economically viable."

Table 3.1. Definitions of Sustainable Manufacturing (or other labels) in the literature (cont.)

Reference	Definition
(Rahimifard and Clegg, 2007) Sustainable design and manufacture	"A responsible approach to design and manufacture of products should embrace efficient resource use by reducing the consumption of non-renewable resources throughout a product's life-cycle."
(Richards, 1994) Environmentally conscious manufacturing	"Minimizing air emissions, minimizing solid and liquid wastes, conserving water and energy, reducing toxicity and not compromising the health and safety of customers, recyclers, and waste handlers"
(Rusinko, 2007) Green or Environmentally sustainable manufacturing	"Taken together, pollution prevention and product stewardship can be referred to as environmentally sustainable manufacturing practices, or environmental sustainability in manufacturing."
(Sarkis and Rasheed, 1995) Environmentally conscious manufacturing	"Environmentally conscious manufacturing, or ECM, involves planning, developing, and implementing manufacturing processes and technologies that minimize or eliminate hazardous waste and reduce scrap. A major objective of ECM is to design products that are recyclable or can be remanufactured or reused. Expected benefits of ECM include safer and cleaner facilities, lower future costs for disposal and worker protection, reduced environmental and health risks, and improved product quality at lower cost and higher productivity."
(Seliger et al., 2008) Sustainable manufacturing	"Sustainability in engineering can be defined as the application of scientific and technical knowledge to satisfy human needs in different societal frames without compromising the ability of future generations to meet their own needs." "Sustainable manufacturing for the next generation should focus on enhancing use-productivity in the total product life cycle."

Manufacturing industry has traditionally been considered as the cause of environmental problems. But it is also recognised as a major enabler for change through economic growth (World Commission on Environment and Development, 1987). The sustainable manufacturing literature focuses largely on design for disassembly, reverse logistics and remanufacturing (Sarkis, 2001; Westkämper et al., 2001; Seliger, 2001; Westkämper, 2002; Srivastava, 2007; Mouzon et al., 2007) since the aim is to keep products within the technosphere when they reach the end of the use phase.

One of the first identified forms of *sustainable manufacturing* in research was *Environmentally Conscious Manufacturing* (ECM), closely related to chemistry, chemical engineering, materials science, and process engineering. Early work in ECM includes considerations for source reduction, dismantling, design for manufacturing and assembly, cradle-to-reincarnation concepts (Owen, 1993). The ECM objectives were defined as "minimizing air emissions, minimizing solid and liquid wastes, conserving water and energy, reducing toxicity and not compromising the health and safety of customers, recyclers, and waste handlers" (Richards, 1994). The challenges of ECM include balancing environmental considerations and other factors such as cost, aesthetics, functional performance, reliability, quality and meeting customer demand (Richards, 1994; Richards et al., 1994). Later, ECM was defined as “the improvement of environmental attributes of product manufacturing, ideally without sacrificing quality, cost, or performance” (Davis and Costa, 1995). The ECM approach as defined by Owen, Richards and Davis focuses on specific material processing and manufacturing operations, and considers individual manufacturing steps in order to decrease their environmental impact independently.

Sarkis et al. proposed a more holistic approach to ECM with the ‘Rs’ strategies for product supply-chain: reduction, remanufacturing, recycling and reuse (Sarkis and Rasheed, 1995; Sarkis, 1995). These strategies aim to reduce the flow of resource consumed as well as create closed-loop circulation of waste as they are reused as resource inputs. The expression *sustainable manufacturing system* began to be used only years later and was strongly associated with the closed-loop circulation of material (Kumazawa and Kobayashi, 2003; Kondoh et al., 2005). This links back to the concept proposed by Frosch and Gallopoulos (1989) although it is rarely named industrial ecosystem. Instead, industrial symbiosis and industrial eco-park are terms more commonly used.

The idea of closed-loop production systems is now more systematically associated with sustainable manufacturing although it can take various forms. Later work focuses largely on product end-of-life management with design for disassembly, reverse logistics and remanufacturing (Sarkis, 2001; Westkämper et al., 2001; Seliger, 2001; Westkämper, 2002; Srivastava, 2007; Mouzon et al., 2007) since the aim is to close the loop of material circulation and to keep products within the technosphere when they reach the end of the use phase. This closed-loop circulation of technical material occurs in parallel (i.e. analogous but separate) to the closed-loop circulation of biological materials in natural ecosystems (Ellen MacArthur Foundation, 2013). Therefore sustainable manufacturing systems can be achieved through carefully designed and managed processes to transform resources into products and services while eliminating and controlling undesirable effects using clean and efficient technologies (Seliger et al., 2008; Allwood, 2005). Resource flows and technologies are the two key elements on which this research focuses.

Under the label of green manufacturing (Rusinko, 2007) and sustainable manufacturing which are considered as sub-concepts of P2, various solutions have been developed for the manufacturing industry to address global environmental concerns. Examples include green supply chain management (Beamon, 1999), product life cycle management (Westkämper et al., 2001), cradle-to-cradle design (McDonough and Braungart, 2002), corporate environmental management (Welford, 2003), design for environment (Bhamra, 2004), product-service systems (Baines et al., 2007), and many others (Sarkis, 1998; Van Berkel et al., 1997). Advances in information technology (IT) have allowed the combined used of these topics to analyse and improve increasingly complex systems (Alvi and Labib, 2001). Many researchers have worked on multidisciplinary approaches to develop more holistic solutions to reduce the environmental impact of business activities using modelling and simulation tools which can capture and manage systems complexity. For instance, discrete event simulation has demonstrated the potential to support the analysis of interactions in complex systems for sustainability in manufacturing (Heilala et al., 2008; Michaloski et al., 2011). There is also an increasing number of tools available to assess the life cycle impact of products and services as well as companies’ environmental performance (Glavič and Lukman, 2007; Ahlroth et al., 2011).

3.2 Sustainable Frameworks and Models for Manufacturing

The concept of sustainability is in part clearly defined and accepted while some aspects of the concept remain the subject of current debates. There are various opinions about the current sustainability level of our society and about what a "sustainable level" of consumption and production is. Some think Earth's carrying capacity is already exceeded; others think there still is a margin to make the transition to sustainability. In all cases, there is a general consensus that changes need to be done to reduce the consumption of resources and not just to improve efficiency of resource (Jackson, 2005; Hertwich, 2005). Technology wedges is a way to approach a "sustainable level" of consumption rather than thinking about a silver bullet technology (Pacala and Socolow, 2004; Sangle, 2011).

A close concept to sustainability is the one of *sustainable development*. The most commonly accepted definition comes from the Brundtland Commission: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development, 1987). The main dimensions for sustainability have also been widely accepted as the so-called triple bottom line or the 3Ps of people, planet, profit (Elkington, 1997): meet societal needs of a growing population while preserving the natural capital for future generations at reasonable cost for the present one. Technology is sometimes considered as the fourth dimension as it is the principal means by which the three first interact and it is a key enabler for change (Jovane et al., 2009).

The Technology-Environment paradox (Gray, 1989) is a central subject for SM since technology allowed healthier, more productive and more enjoyable lives whilst simultaneously threatening life on Earth due to unforeseen consequences of technology use (Graedel and Howard-Grenville, 2005). Technology determines the efficiency with which the resources are used in society and therefore is often considered as an additional dimension to the traditional three dimensions of sustainable development (Jovane et al., 2008; Lovins et al., 1999). Seliger puts it another way and argues that manufacturing industry is responsible for the environmental efficiency of our society and technology (Seliger, 2007).

Two other important concepts for sustainability are the *precautionary principle* (Robèrt, 2000) and *decoupling* (Cleveland and Ruth, 1998). These concepts are linked and overlap. Decoupling of environmental and economic growth is key to reduce the burden of human activities on the environment while providing good life standard to all. A major difficulty in the dissemination of sustainable manufacturing practice in industry is the duplication of concepts, and thus efforts, as well as the lack of understanding on what is the global impact of local improvements, which is called the *rebound effect*. For example, efficiency gains can have counter-intuitive results if they are not accompanied by policies to control their consequences and to avoid the direct rebound effect where expected savings are partly offset by increased consumption (Jin, 2007). Another similar effect is the *backfire effect*, where the efficiency improvement measures are completely offset and the total energy use actually increases. For instance, energy efficiency improvements in automobiles have led to increased usage which in turn has increased the total amount of energy consumed by cars. Subsequently, end-of-pipe solutions (such as the catalytic converter) have been used reduce the impact of the waste gases. But the causes of the problem remain and new measures to reduce the pollution at the source (pollution prevention, precautionary principle, green design, etc.) have to be taken.

Sustainable manufacturing is a broad concept and covers the areas of product design, supply chain management and customer-oriented approaches and adopt a lifecycle perspective which enables more integrated thinking on how to change the design of products and production systems in order to reduce their environmental impact in the most efficient way (Seuring and Müller, 2008; Vachon and Klassen, 2008; Baines et al., 2009; Tan et al., 2010). Minimising manufactured products' embodied energy is attracting more and more attention as energy cost is increasing as well as the associated environmental impact (Rahimifard et al., 2010). Beyond energy efficiency in manufacturing, the assessment of embodied energy encompasses more than energy directly related to the lifecycle of a product: it shows the importance of material choice and supply chain parameters (Kara et al., 2010).

There are numerous levels to consider when investigating sustainability in manufacturing. Sustainability improvements must consider issues at all levels in the industrial system: process, product, and system. Activities at any of these levels must be considered in its wider context and not in isolation, i.e. consider impact on all other levels else improvements can be suboptimal. One must keep an eye on the wider system to ensure that local solutions are not creating larger problems or result in a rebound effect.

Processes were the first target of attention with the concept of P2 (Graedel and Howard-Grenville, 2005). At the process level, technology and production management (planning and control) are improved to reduce resource use (energy and material, including water) and undesired outputs (toxic wastes, pollutant emissions to air, water and soil).

Then, attention was brought to the design of products which determine most of the environmental impact throughout the product life cycle (Müller et al., 1999; Haapala et al., 2008). Then the next levels to consider are material selection, resource extraction and processing (Brunner and Rechberger, 2004), the value chain to provide goods and services (Maxwell and Van der Vorst, 2003). Although it is widely recognised that design decisions impact the whole product life cycle and supply chain (Heilala et al., 2008; Müller et al., 1999), they are not well integrated with the design of production systems (Ball et al., 2009).

At the system level: life cycle perspective considers the whole supply chain, product end-of-life with the infrastructure, and wider involvement of all actors to achieve this. Given that system scale and complexity is ever increasing, it is crucial that all the above-mentioned levels are considered for sustainability in industry and to ensure that the solutions are optimised at all levels. Considering the material life cycle, a common concept is the 3Rs (reduce, reuse, recycle) later extended to the 6Rs (reduce, reuse, recover, redesign, remanufacture, recycle) concept which have been adopted for sustainable manufacturing (Kutz, 2007). The next paradigm shift will focus on transforming the traditional single life cycle and open-loop circulation of materials to multiple life cycle and closed-loop circulation. Industrial ecology biological analogy and Ricoh "comet circle" for green supply chain (Ricoh, 1994): There are many ways to close the loop of material, but the smallest loop being the most desirable as it will require less resource to retain the value of the product and get it back to the user. In this research, the focus is on the resource flow in the factory and therefore the same concept is applied at factory level instead of including wider elements.

3.3 Tools for Sustainability

The previous section has presented concepts and perspectives for sustainability. Many child-concepts have been developed to support sustainable development at various levels of activity, such as industrial ecology (Frosch and Gallopoulos, 1989) and cradle-to-cradle design (McDonough and Braungart, 2002). Other research fields for industrial sustainability are developing and rapidly growing, such as Product-Service Systems (Baines et al., 2007) and whole supply chain integration with the design of products and production systems (Srivastava, 2007; Haapala et al., 2008). These concepts can be difficult for industry to translate into practical measures. While it is important that all companies keep a holistic vision on objectives that are consistent with the definition of sustainability, the implementation of sustainability activities is proper to the systems specificities, conditions and current state of performance.

Existing tools for environmental performance evaluation and improvement can be sorted into four categories (Glavič and Lukman, 2007; Robèrt, 2000; Baumann and Cowell, 1999; Finnveden and Moberg, 2005).

Table 3.2. Tools for environmental performance evaluation and improvement.

1) Assessment, monitoring and inventory tools	These tools are used to quantify the system's performance and to identify issues, i.e. areas of improvement.
2) Engineering, design and improvement tools	These tools are used to generate improvement options to address a specific issue.
3) Environmental policies and enforcement tools	These tools provide the structure and favourable conditions to incentivise the implementation of improvements.
4) Prioritisation, management and decision-making tools	These tools are used to specify the procedure for implementing improvements.

Selection of the appropriate tools must take into consideration the object of study and the types of impacts of interest (Finnveden and Moberg, 2005). These four categories reflect the different topics considered and steps needed to move towards sustainable manufacturing. The first step is to quantify the system's performance (assessment tools). The next step is to set targets and determine what the options are to improve the system (improvement tools) and finally to choose the best option to achieve the defined targets (decision-making tools). An additional element to consider is policies and regulations (enforcement tools) which have a strong influence on decision-making.

Sustainable strategies and policies (Kerr, 2006) as well as supporting metrics (Figge et al., 2002; Labuschagne et al., 2005) to assess performance and quantify the contribution to the triple bottom line—people, planet and profit (Elkington, 1997)—are well-developed. Policy and enforcement tools are crucial to promote and encourage the implementation of environmental performance improvements. Policy instruments can either be used as minimum standards or as guiding principles to go beyond regulatory levels. They can be local policies used internally by individual companies (Midilli et al., 2006) or economy-wide to support the development and implementation of sustainable technologies (Sandén and Azar, 2005). Typical policy options (Kolk, 2000) are regulations such as emissions and technology standards or materials prohibition; financial incentives and disincentives in the form of subsidies for research, effluent taxes and waste disposal fees; marketable permits such as CO_2 emissions permits and tradable offsets; and voluntary agreements, target setting and planning.

In order to set targets and move towards sustainability, one must first understand the impact of the business on the environment, i.e. it needs to be measured. Sustainability performance assessment looks beyond classic economic factors (payback time and return on investment). Societal improvement, carbon footprint reduction and efficiency improvement need to be taken into account. There is a multitude of assessment tools and indicators available to quantify performance and progress such as life cycle assessment (LCA) (Baumann and Tillman, 2004) and material flow analysis (MFA) (Brunner and Rechberger, 2004). Other tools such as ecological footprinting (Wackernagel and Rees, 1996) and sustainability indicators (Hak et al., 2007) are multi-dimensional and can account for social, economic, environmental impacts, water, energy, materials, greenhouse gas emissions and whether the product is recyclable or reusable.

In particular, LCA is a fundamental assessment tool to evaluate the environmental impact of a product across its entire life. It is clearly defined and its use standardised (ISO Life Cycle Assessment guidelines). However, the requirements in terms of money, time and data collection effort are significant. Similarly to other tools, the complexity of the LCA methodology can be prohibitive (Ahlroth et al., 2011). This often prevents the application of a complete LCA and limits the application to a (subjectively) simplified version which can provoke controversy: some companies are using simplified LCA to prove the superiority of their product over competitors' ones by making "convenient" assumptions. Some rigorous methodologies for simplified LCA have been introduced to avoid such misuse of the tool (Mori et al., 2000).

Assessment tools can also be used with management tools to prioritise improvement options and make informed decisions about product design, distribution and use. They encourage accounting for all resources, including not only material for the manufacture of a product but also energy and consumables, in Life Cycle Costing (LCC)—an important driver for sustainable manufacturing. The integration of environmental considerations must occur during the earliest stages of product design as decisions taken early have a greater impact on the overall system's performance (Müller et al., 1999; Keoleian and Menerey, 1994). This is typically the case with process-oriented and product-oriented P2 which contrasts with the end-of-pipe approach. P2 improvements include eco-efficiency (Kuosmanen and Kortelainen, 2005), dematerialisation (Cleveland and Ruth, 1998) and substitution (Lifset and Graedel, 2002). A typical improvement tool for the design stage is Design for Environment (DfE, also called eco-design) which is a popular approach for environmental performance improvement. DfE integrates environmental considerations over the life cycle of the product in the early stages of product design (Allenby and Richards, 1994). Similar concepts are Design for Assembly and Disassembly, Design for Recycling or Recovery, which are often referred to as Design for X strategies or DfX.

As illustrated by LCA and DfE, existing tools for environmental performance evaluation and improvement are well developed; but they focus on products and encompass more than what a manufacturer has immediate control over. Manufacturing system design tools are notably absent here, especially when considering the boundaries of gate-to-gate where individual companies' opportunity to improve through immediate control is highest. Techniques and supporting tools tend to be discipline specific and tend not be used across boundaries. For instance, techniques for production system analysis are deployed separately to those of building systems and facilities management. These areas are all generally within the full control of companies and have potential to benefit from an ecosystems view that could provide opportunities to remove local optimisation and to have shortest path closed loops such as energy reuse.

Advances in information technology, more powerful tools have been developed to support P2 in early design stage (both for products and processes). These tools enable the modelling, simulation and analysis of interconnected, complex systems such as production systems. Various modelling and energy analysis tools have shown possible to provide tangible benefits towards sustainable manufacturing (Gutowski et al., 2009; Heilala et al., 2008; Michaloski et al., 2011; Herrmann and Thiede, 2009; Fröhling et al., 2012). While these tools are helpful to support improvements, they do not provide a practical approach and overall structural framework for the users across functions to identify inefficiencies or improvement options for resource efficiency. Therefore, guidance is required on how to achieve sustainable improvement in manufacturing.

3.4 Chapter Summary

It is now widely recognised that the natural ecosystem capacity to produce resources and assimilate waste is exceeded. It is becoming urgent to make a major shift in the way we produce goods and consume resource. Manufacturing is responsible for the efficiency with which resources are transformed from raw material to economically valuable goods and therefore has an important role to play in the move towards a sustainable society. Sustainability and Sustainable Development are well-established concepts. They are commonly viewed as multidisciplinary since they are composed of three, sometimes four, dimensions: society (people), environment (planet), economy (profit), and sometimes technology (Jovane et al., 2008; Elkington, 1997; Lovins et al., 1999). This research focuses on the environmental dimension and considers technology as a means to reach sustainability objectives. Social and economic aspects are positive side-effects of the environmental activities undertaken in the industrial system.

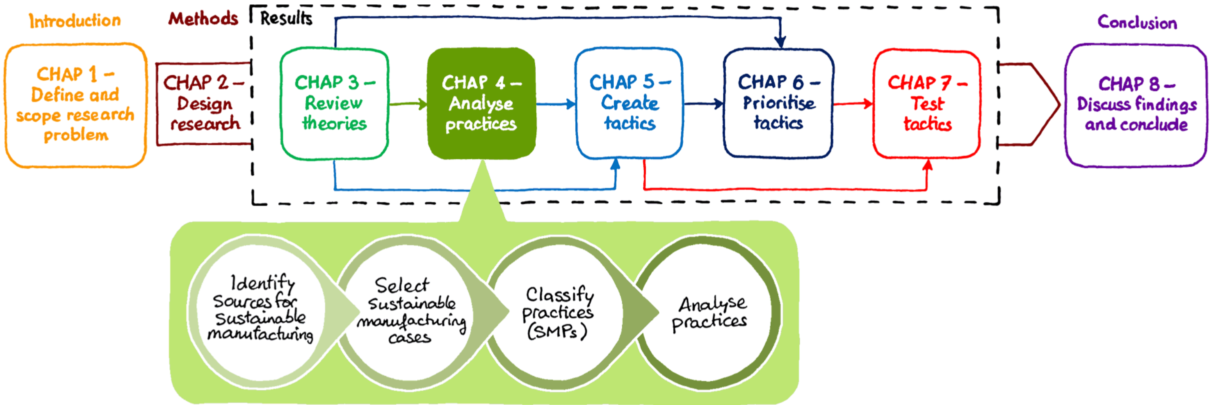
Other well-established concepts and approaches addressing environmental issues at a systems level include industrial ecology (Graedel, 1994), green supply-chain management (Beamon, 2008), and the ‘Rs’ strategies of *Reduce-Reuse-Recycle* (Sarkis and Rasheed, 1995). Although the volume of literature in the area of industrial sustainability is growing quickly, there is a gap in guiding manufacturing companies to bring sustainability into practice. The next chapter reviews industrial practices in order to understand the link between high-level concepts and improvement practices conducted in the manufacturing industry.

The literature also highlighted the need to systematise improvement activities in manufacturing using tools which can support manufacturing companies in analysing their current performance and improving it. A wide range of tools have been developed to assess the environmental impact of industrial activities and to change the way products are manufactured and the way services are provided to customers (Robèrt et al., 2002; Allwood, 2005; Seliger, 2007; Graedel, 1994; Ayres and Ayres, 2002). These tools for environmental performance evaluation and improvement are well developed, but they are insufficient to use in their current form to support factory improvements, failing to offer a process rather than product perspective. This research supports the development of such a tool as introduced in Chapter 7.

Chapter 4 SUSTAINABLE MANUFACTURING PRACTICES

Part of this chapter has been published in **Despeisse, M., Mbaye, F., Ball, P. D. and Levers, A. (2012), "The emergence of sustainable manufacturing practices", *Production Planning & Control* 23(5), pp. 354-376** of which the thesis author was the main contributor.

The area of sustainable manufacturing is rapidly gaining the interest of manufacturers. But yet there are few quality reports on current levels of sustainable manufacturing activities in companies. In this chapter, industrial practices for more sustainable manufacturing are collected from various sources and analysed to give an insight into the application of the concepts and approaches found in the literature. The initial theory building is described to show how the findings were obtained from the analysis of these sustainable manufacturing practices.



4.1 Introduction

4.1.1 Focus of this chapter

Sustainable manufacturing can be thought of as a manufacturing strategy that integrates environmental and social considerations in addition to the technological and economic ones. Environmental activities have long been associated with a negative impact on business performance but this assumption has been proved wrong by many researchers (Rusinko, 2007; Menzel et al., 2010). An illustration of both the economic and environmental benefits is apparent in the cost savings due to energy reduction and waste minimisation. Sustainable manufacturing field of research is rapidly developing and there are no established definitions or boundaries for studying manufacturing systems' sustainability performance.

This chapter focuses on the environmental aspects of sustainable manufacturing practices with an emphasis on on-site solutions rather than 'product life cycle' or 'product supply chain'. In particular the work focuses on how resource efficiency improvements within a manufacturing system were achieved and proposes an approach by which these improvements can be examined and classified. Thus the researcher chose a cross-sectional case study method. Cases were collected from various sources dedicated to the topic of manufacturing operation improvements for environmental sustainability. Cases were then divided into individual sustainable manufacturing practices (SMPs) defined as an action or set of actions improving the manufacturing system's environmental performance. The practice analysis resulted in the identification of improvement mechanisms which will be used in the next chapter to formulate the generic tactics and allow the generalisation of SMPs across industry.

4.1.2 Objectives and deliverables

A total of 967 SMPs were collected and analysed (peer-reviewed: 38 cases from which 165 practices were extracted; specialised websites: 207 cases, 802 practices). The complete database of practices is available in appendix. The collection and analysis of practices was done in three phases.

The researcher conducted a first data collection during a previous study in 2009 to create the structure of the database which was further populated collaboratively with a MSc student[2] to reach a total of 210 practices from 60 source cases (Despeisse et al., 2012c). The A-, B- and C-labels emerged from this original case collection and analysis. The second phase of the data collection was conducted as part of the THERM project: further cases were collected by a third party[3] to reach a total of 650 practices (from 150 source cases). This second phase helped to improve the terminology used to formulate tactics (Chapter 5) and improve the structure of the library of tactics (Chapter 6). Finally, a third collection phase was conducted by the same third party as part of the THERM to check for completeness of the SMPs coverage. With 300 additional SMPs collected from ~100 source cases, no further tactics were identified. Therefore the case collection was stopped and the resulting database of SMPs was used to validate the final tactics library.

This chapter reports the findings of all phases of the cross-sectional case study:

- Selection of sources for the case collection as they offer different types of information on SMPs;
- Analysis of industrial case reports revealed that the terminology and interpretation change depending on the source of information and scope of activities;
- SMPs categorisation and introduction of various sets of labels (categorisation criteria) used to structure the SMPs database and ease the subsequent analysis;

4.2 Sourcing, Selecting and Interpreting Case Study Reports

4.2.1 Sustainable manufacturing cases sources

The data collection focuses on environmentally-sound practices in manufacturing. As these practices are increasingly common and more often reported since the late 1990s, the volume of information and the diversity of sources are ever increasing in academic publications and trade literature. This growing body of knowledge and information is difficult to fully capture. Therefore it is important to clarify the purpose of the data collection and to carefully target the relevant information for this purpose. This case collection aims to identify the mechanisms of improvement for sustainable manufacturing in two steps. First the different types of existing activities for sustainable manufacturing must be recognised. In other words, the case collection must focus on the breadth of the landscape of SMPs, but not necessarily a large number SMPs or a statistically representative sample. This would be useful to identify the most common practices or to analyse trends in various industrial sectors or in specific performance improvement. Instead the main mechanisms of change need to be identified. Thus the second step consists of identifying patterns and extracting the generic principles for sustainable manufacturing improvement so it can be generalised across industry by removing

[2] Fatou Mbaye, MSc student at Cranfield University (Mbaye, 2009).
[3] Ioannis Mastoris, employed by Cranfield University for the THERM project (2010).

the context-specific elements of the practice. In turn this can help manufacturers to improve their sustainability performance by replicating other companies' SMPs.

Sources are diverse and given the exploratory nature of the work, trade literature was used in addition to academic sources. Interestingly, academic and trade literature provide complementary aspects and perspectives on SMPs. The academic publications containing SMPs include journals, books and conference proceedings on various sub-topics of sustainability such as eco-efficiency, cleaner production, industrial ecology and waste management. Trade literature considered for data collection includes corporate websites, environmental and sustainability reports, good practice repositories on organisational and governments' websites dedicated to specific issues such as energy efficiency, boilers and motors for steam and compressed air systems, or water treatment.

4.2.2 Case selection

The selection of industrial cases for the analysis was based on the nature of the information reported. Cases were selected to only include the ones allowing a consistent and precise analysis of practices reported. One of the major difficulties encountered was on the terminology used in the reports. This issue will be discussed in the next sub-section. Publications presenting only conceptual approaches or anecdotal evidence were excluded. The cases must also contain sufficient amount of details to make objective observation and interpretation of the activities having a direct effect on sustainability performance. Additionally cases reporting off-site solutions or involving the intervention of external actors, such as off-site recycling or purchase of renewable electricity, were also excluded. Some cases containing purely organisational measures (training, workshop, raising awareness, creation of responsibility for sustainability issues) and health & safety measures were included in the database of practices but not analysed. They are an important part of the implementation process by actively engaging employees in the projects while ensuring minimum risk for workers. However, they were not taken into the next steps for analysing practices: they do not correspond to any direct effect on sustainability performance of resource flow and technological components of the model.

Organisation and government's websites were used first as they were the most convenient sources to access and the cases reported the easiest to capture. They provided libraries of reports containing manufacturing companies' best practices. The format of these reports was consistent, which was a great advantage for collecting data across all cases. They also contained sufficient amount of details to understand what the company did and what the benefits of implementation were. The emphasis of these reports was on the return on investment and savings accomplished rather than on informing the reader how such good practices could be reproduced elsewhere. Despite this lack of information, cases from organisation and government's website were selected for the case collection.

Corporate reports and websites, such as environmental pages of brand name manufacturers, were also considered as a potential source of cases. They provided few cases and hardly any technical details on the activities. Again, the focus was on the positive impact for conducting sustainability projects for the environment, the local community and employees, and of course for the business. The reports provided insufficient details to clearly understand what the company did and the benefits reported did not offer an insight to track back the means by which the performance was improved. Although these reports and websites were encouraging and showed that sustainability can pay, they were not selected for the case collection.

Finally, peer-reviewed sources presented approaches or examples of SMPs based on surveys or analysis of industrial practices with some occasional company cases. Books and journals on specific topics, such as waste management, also offered numerous insightful practices. As with the other sources, they rarely provided information about how the improvements were identified at the first place. Moreover they often contained fewer details on the technical content of the activities. In comparison, companies' best practices from specialised websites provided quantitative data on the equipment, inputs and outputs, and the benefits from the implementation. Journal papers occasionally contained such quantitative details when related to specific manufacturing processes in case studies. Most often academic sources offered a wider range of practices at once compared to other sources and consequently were selected for the case collection.

4.2.3 Terminology and interpretation

To find potential data sources and publications, the search keywords used were purposefully broad and generic at first (see Table 4.1). These keywords came from the literature review and correspond to the key concepts and themes related to sustainable manufacturing. Using various scientific database and classic web search engines, the number of hits was extremely high. However, sorting the search results by relevance allowed the identification of main sources of information. Only later as the case collection progressed and the researcher learnt from the first observations, more specific keywords were used to narrow down the search to more likely relevant cases (see Table 4.2). As the keywords were generic, the search spanned across industrial sectors and tried to capture a wide variety of activities. The number of hits for certain combinations of keywords was still very high. Therefore further filtering and selection of relevant cases was required.

The second set of keywords in Table 4.2 allowed the researcher to target more specific areas to complete the case collection using academic publications. The first column limits the search to the disciplines related to environmental sustainability, the second identifies the manufacturing industry, the third filters cases, the fourth narrows down to specific improvement targets and the fifth describe the type of activity. Keywords from the three first columns were systematically included in searches and usually gave more than 1,000 results. The last two columns were used further narrowed down the results. When the number of hits remained above 100, results were filtered using the database search tool by selecting or excluding certain source titles or subject areas (such as medicine), or alternatively by searching only among papers' keywords.

Table 4.1. First set of search keywords to identify potential sources

Concepts and themes used as keywords
sustainable manufactur*, environment* conscious manufactur*, environment* responsible manufactur*, green manufacturing, clean* production, industrial ecology, eco-efficiency, resource productivity, dematerialisation, material substitution, energy efficiency, waste management, water conservation

Table 4.2. Second set of search keywords to narrow down the search

Discipline	**Sector**	**Filter cases**	**Target**	**Type of activity**
sustainab*, responsible, pollution prevention, environment*, green, clean, eco-friendly, low-*,zero	industr*, production, manufactur*, process	case, practice, application, implement*, example	energy, material, waste, water, air, carbon, emission	avoid*, eliminat*, reduc*, minimis*, reus*, recycl*, recover*, conserv*

In the trade literature (organisations, government and corporate sources), the libraries of best practices were accessed via short articles or longer reports. An observation of the terminology used in some of these sources revealed a partial mismatch with the vocabulary used in academic literature on sustainable manufacturing. A typical example is the use of P2 for effluent treatment practices in trade literature when this would be labelled *pollution control* in peer-reviewed literature. A second example is the use of *waste recycling* for any kind of waste treatment other than landfill in corporate cases, including *energy recovery through incineration*. In contrast peer-reviewed literature would more often exclude *waste-to-energy* as a recycling activity due to the destructive nature of this type of material treatment. Peer-reviewed literature also differentiates the various options for closing the loop of material: *reuse*, *remanufacture*, *recycle*, *upcycle* and *downcycle* depending on the path taken by material for its next life cycle. The terms *reuse*, *recover* and *recycle* are often used as synonyms to cover all these options in trade literature.

Another difference in terminology within academic literature was also observed during the literature review and helped develop the second set of keywords. Depending on the perspective of the publication, different vocabulary and definitions are used. There are considerable debates on the use of *sustainable* as an adjective as it is argued that it could mean anything the user wants. For instance, some authors consider that one cannot use *sustainable* if the primary focus is on only one or two of the three pillars of sustainability (environmental, social or economic). The title of this research illustrates the debate well: the term *sustainable manufacturing* (rather than *environmentally conscious* or *green manufacturing*) is used although the primary focus is on the environmental impact linked to resource extracted from and emissions released to ecosphere. However, the overall purpose of the research has wider implications for the economic and social performance of the company (see Chapter 1). Consequently, the researcher chose to keep the word *sustainable* to explicitly show her considerations for social and economic issues while focusing on improving the environmental performance.

Finally a terminology inconsistency can be found depending on the theme and scale of the activities reported. Taking the example of P2 once more: when considered as an approach by itself, it means local on-site solution only; but when considered as a subset of industrial ecology, it may include off-site solutions with the concept of food web and industrial eco-parks. This distinction has been discussed by various authors (Van Berkel et al., 1997; Oldenburg and Geiser, 1997). Therefore there is a challenge in linking the cases to theme and concepts in sustainable manufacture and in turn could be a source of error (or at least bias) when selecting, categorising and analysing the cases.

4.3 Categorising Practices

After sources were identified and cases selected, each case was broken down into individual practices. The cases selected for this analysis presented examples of good practices carried out to improve the sustainability performance of manufacturing operations. The focus is on practices conducted on-site, involving physical changes (as opposed to behavioural) and sufficiently detailed to understand what was done. Each case was then broken down into individual practices (or SMPs) as one case usually contains many activities improving the manufacturing system's environmental performance. For example the first case collected ("Compressed Air System Improvements Increase Production at a Tin Mill") was focus on a single system but contained three practices which contributed to the performance improvement. This case reported a *compressed air system improvement* achieved by (1) leak reparation, (2) installation of new compressors to replace old compressors with new high efficiency ones, and (3) installation of a new compressor sized for a specific process demand. Each practice gives an example of what a company can do to achieve compressed air system improvement. In other cases, practices were interrelated as for instance with (1) waste collection and treatment enabling (2) reuse; or (1) improving controls with (2) the installation of new equipment.

Individual practices could be categorised as they have distinct features which help understanding the *mechanism of change*. Groups of similar practices were established based on these features. The practices were then mapped against sets of labels. These labels helped to understand how the resource efficiency was improved:

- A-labels correspond to the system **A**LTERATIONS, e.g. describe the type of modification (technical or physical *change*, organisational or operational *manage*) and the elements targeted (focus on *resource flows* or *technology*);
- B-labels correspond to the targeted **B**ENEFITS and link to **B**EST PRACTICES, e.g. describe the nature of the flow affected by the practice (inputs: energy, water, material; outputs: air emissions, wastewater, solid waste);
- C-labels correspond to who **C**ONTROLS the improvement activities, e.g. describe the functional responsibility to implement the SMPs in the factory.

Each set of label correspond to a different perspective on the improvements presented in the cases. The next sections present in more detail the perspective adopted by describing the criteria of categorisation and their purpose / how they can be used.

*4.3.1 A-labels: **A**LTERATIONS to processes and resource flows*

Adopting the ecosystem view of manufacturing activities, each practice (improvement of a given system) can be represented by a simple diagram using box objects for technological components (equipment, machine, process) and arrow objects for resource flows. The ecosystem view particularly focuses on the resource flows and considers technology as the transformation process of these flows from one form (input) into another (output). The useful output is called product, whether it actually is the manufactured part, assembled product or energy utility from a facility process. Waste corresponds to all other outputs, including losses in the form of noise, waste heat radiating from processes or emissions to air or water from chemical processes. It is important to note that waste flows are considered as potential resources unless they are not recoverable or when they leave the boundaries of the system.

Some elements such as catalyst chemicals can be considered both as a resource flow or part of the technological component. In effect, the catalyst plays the role of modifying the resource flow in the same way technology does except that it flows with the product: it is an input to a process and comes in an unchanged form as an output. The same can be said of packaging: its role is to ensure transport of material from one point to another and eventually to protect to the product. It becomes a waste output which can be reused either directly or after treatment to restore the value of the material and allow reuse.

In this categorisation, practices were not clustered according to classic criteria such as operational characteristics or functions, but on the model representation of the system and the way improvements modified the model. The method used four clusters (called A-labels, A1 to A4) corresponding to the type of modifications, e.g. system **A**LTERATIONS made to the model representation as illustrated in Figure 4.1. The four A-labels correspond to the type of modification and the components targeted. The A-labels were the most powerful to code SMPs and thus were used to structure the tactics library (Chapter 5).

As identified in the literature review (Chapter 3), the two main technical improvement approaches identified are technological change and process management (Gupta and Cawthon, 1996; Raymond et al., 1996). Therefore the two types of modification possible are: change system's components (CHANGE: add, replace or remove) or change the parameters of an existing component (MANAGE: timing and magnitude, e.g. operating time and set points). Additionally, there are two types of components: physical infrastructure and utilities considered as technological components (TECHNOLOGY: processes, machine/equipment, group of machines or processes), and all inputs and outputs considered as resource flows (RESOURCE: material, energy, water, chemicals, waste, etc.). Consequently the four A-labels are: A1 Manage Resource, A2 Change Resource, A3 Manage Technology and A4 Change Technology. The A-labels were the most useful to understand the mechanism of change observed in the SMPs and therefore were used as a basis to structure the initial library of tactics.

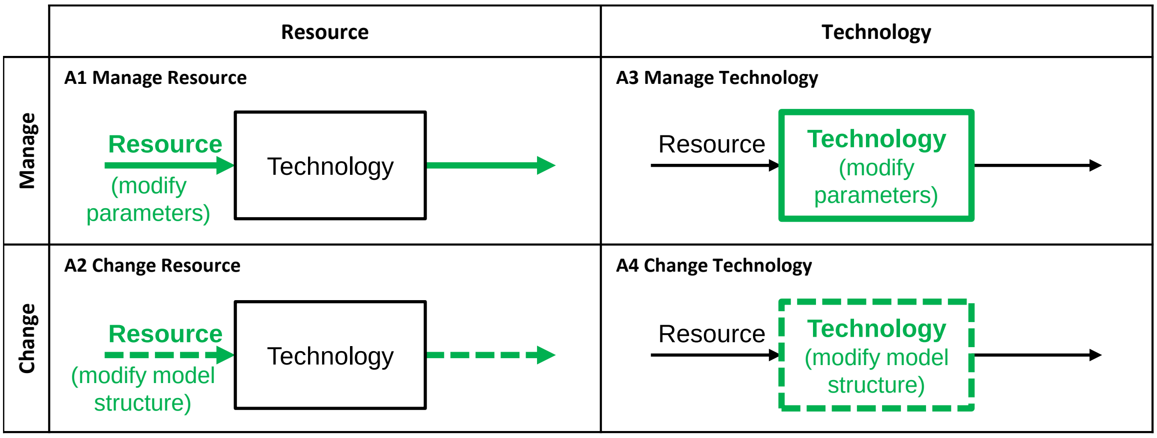


Figure 4.1. Four A-labels and model modifications

*4.3.2 B-labels: targeted **B**ENEFITS and **B**EST PRACTICE categories*

The B-labels correspond to the targeted **B**ENEFITS, e.g. the nature of the resource flow affected by the SMPs, and link to **B**EST PRACTICES. These are the most generic description of inputs and outputs flows corresponding to the main environmental impacts: resource depletion, water scarcity, and air, water and soil pollution (Salvato et al., 2003). Although there are sector-specific environmental considerations, all environmental impacts are treated in the same way in this analysis. It is up to the user to make a decision regarding the prioritisation among different environmental improvements based on their targets (energy reduction, CO_2 abatement, zero waste, etc.). Emissions, wastes and resource usage must be monitored for regulatory purpose, but they can also help identify inefficiencies and areas requiring improvement.

Reducing costs associated with energy and material inputs has long been low priority but the trends in raw materials and fuel prices have changed this perception. Improving resource efficiency has proved to be a cost-effective method in most cases. Thus *energy* and *material* were selected as classification criteria in the B-labels.

Energy can be further categorised into groups of fuels (electricity, gas, renewable, etc.) or end-users (electrical appliances, heating and cooling, etc.). Energy can also be an output (waste energy), but the B-labels do not differentiate it from energy input as energy is readily available for reuse as input, whereas solid and liquid forms of waste usually require treatment. Instead, the negative output or undesired environmental impact associated energy consumption is the direct and indirect emission of airborne pollutants. Direct emissions result from the combustion of fossil fuels generating CO_2, SO_X, NO_X, particulate matter (PM) and other gases that cause atmospheric pollution and significantly contributes to global warming. Indirect emissions are associated with electricity consumption depending on the energy mix at the source (energy supplier). The benefits from energy efficiency improvements are directly linked to emission reductions and thus *air emissions* was chosen as a classification criterion.

Material or matter can be classified in groups sharing similar properties: metals, polymers (or plastics), semiconductors, ceramics, composites, etc. For manufacturing, the two dominant material groups are metals and plastics which are part of the manufactured product. The consumable materials (before it becomes waste) which are not part of it are treated similarly whatever group they belong to and therefore are under a separate label (consumable). Matter does not have to be solid. It can also in any other form; therefore water and air are also materials. However, water is taken separately as it benefits from special treatment aside from the common one previously cited. Thus *water* and *wastewater* are separate classification criteria.

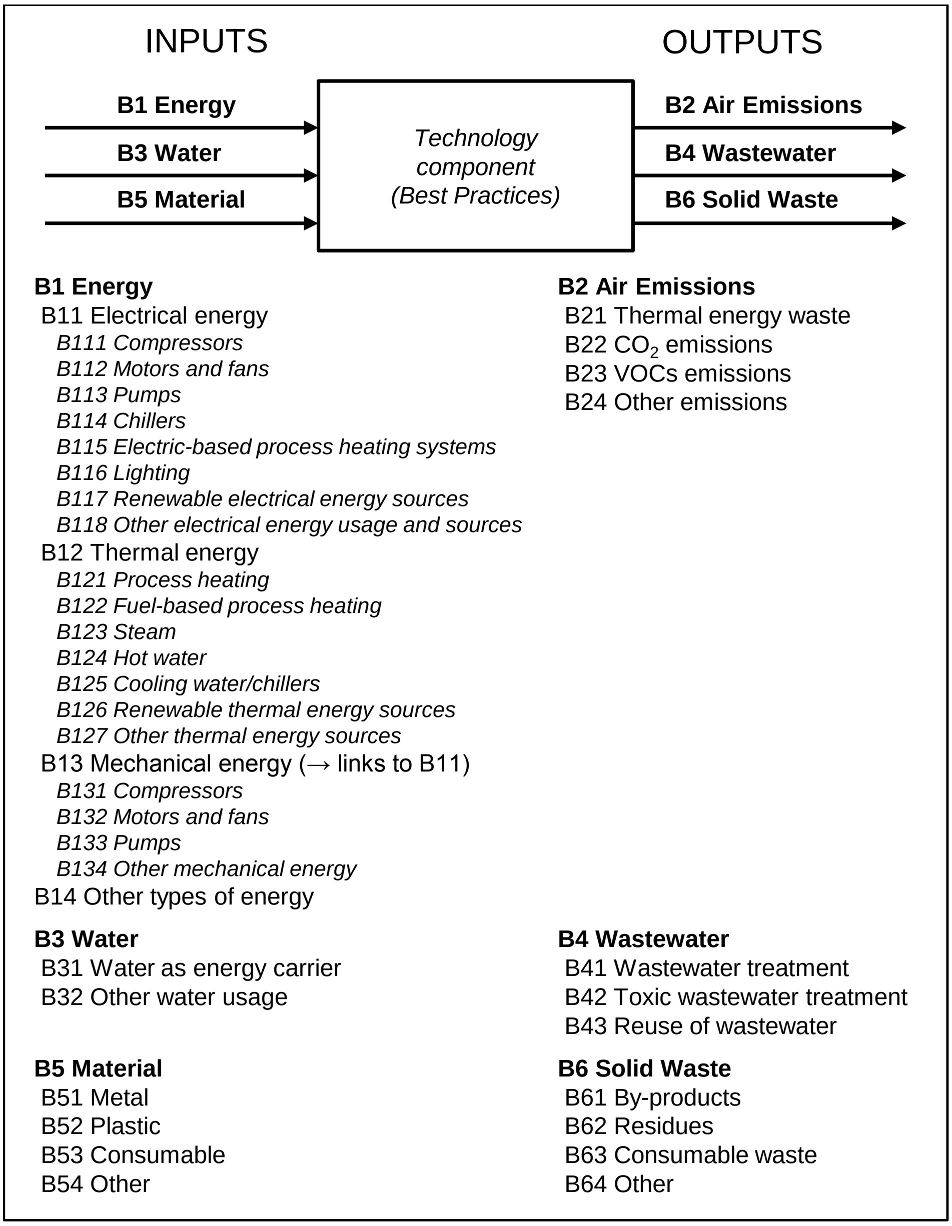


Figure 4.2. Six B-labels and examples of categories for each, and sub-categories for B1

The six B-labels are shown in Figure 4.2. The B-labels for input flows are: B1 Energy, B3 Water and B5 Material; and for output flows: B2 Air Emissions, B4 Wastewater and B6 Solid Waste. It is possible to create more detailed categories under each B-label to further specify the flow type and subcategories for best practices as proposed with *B1 Energy* in Figure 4.2. The purpose of this B-label classification was to allow access to specific practices based on the targeted benefits (energy reduction, CO_2 emissions abatement, water conservation, toxicity, “zero waste”, etc.) as well as allowing a keywords search when looking for practices related to specific technologies. Therefore the B-labels relate to specific technologies and resource types and were not used for the creation of the library of generic tactics.

*4.3.3 -labels: **C**ONTROL over improvement activities*

Finally, the eight C-labels shown in Figure 4.3 correspond to the functional responsibility, e.g. who has **C**ONTROL over the area of improvement. The purpose of the C-label classification is to narrow down the search for practices to specific functional areas of the company according to the responsibility of the people involved in the improvement activities. Some practices could be carried out by a single function (e.g. facility maintenance) while others can involve multiple functions (e.g. factory-wide change such as modification to compressed air supply pressure or cooling water temperature). This is an important aspect of practice implementation as functional responsibility can be a barrier if the practices are affecting elements outside the area on which they have control. Similarly to the B-labels, the C-labels were not used for the creation of the tactics library.

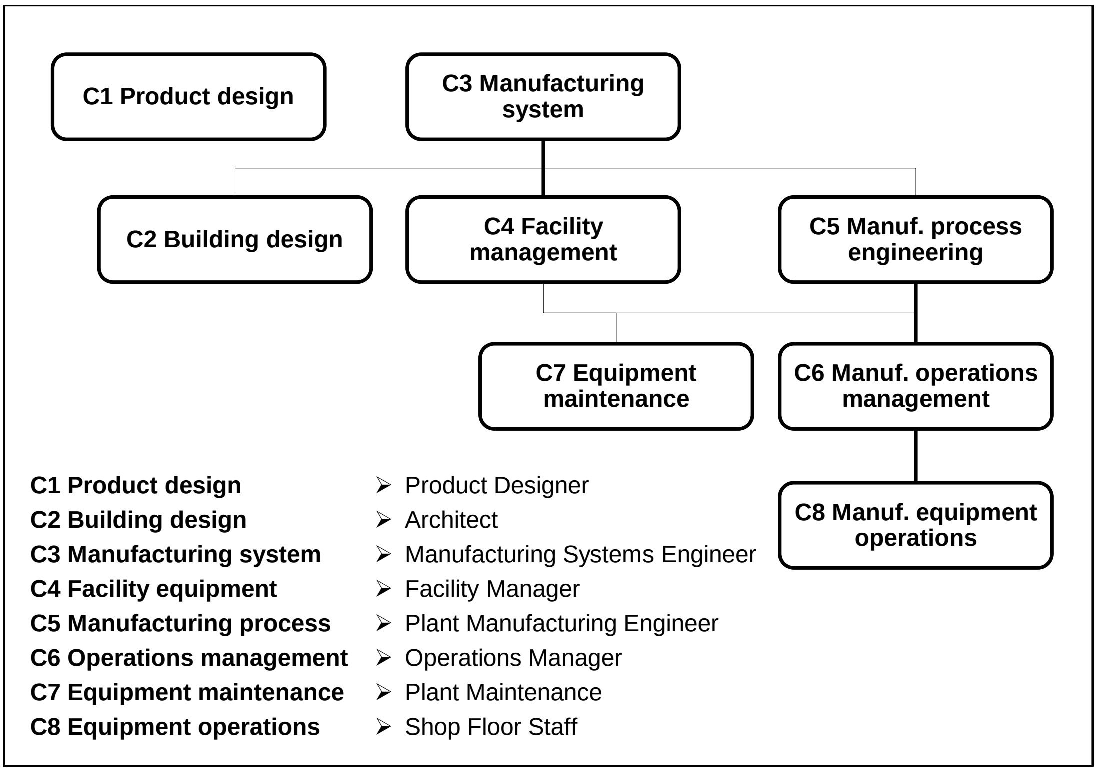


Figure 4.3. Eight C-labels and responsibility hierarchy

4.3.4 Other potential criteria

Classification based on complexity was first considered: magnitude of change would be assessed based on the number of system elements involved in the improvement, i.e. two or less elements involved in the improvement would correspond to a “minor” change while three or more elements involved in the improvement would correspond to a “major” change. However this classification would be highly dependent on the way the system is represented: one element can represent a process composed of five pieces of equipment and therefore the improvement, although involving only one element and thus classified as “minor” change, could affect more than three machines and in effect would become a “major” change. In addition, the complexity of an improvement can also be highly subjective: modifying process controls can be considered as a simple modification on equipment or process management but be considered as a complex change for the company as it may result in further changes on other processes.

D-labels based on economic aspects were also considered. These labels are based on initial investment cost and/or payback time. This classification is highly subjective as the definition of “low” or “high” financial requirements differs from one company to another. A solution to this subjective classification was to create an intermediate D-label “medium” which allows the user to evaluate the financial requirements based on personalised criteria. However this D-label classification was removed due to the difficulty in classifying practice in “low” or “high” which resulted in the majority of collected practices to be in the “medium” class. The only way to make sense of this “medium” class would be to include a threshold value so that the user could filter practices based on his personalised criteria. But this filtering requires a systematic quantification of the cost of improvement for all practices when only a minority of them contained such information. Therefore the D-label classification was considered of poor usability.

4.4 Analysing Practices

Industry is one of the single largest energy consumers with 20% of the final energy consumption in the UK and 25% in the European Union (Eurostat, 2012). Reducing costs associated with energy has long been low priority but the trend in energy price has changed this perception. Improving energy efficiency has proved to be a cost-effective method in most cases through good housekeeping. Other areas in manufacturing facilities and buildings are being targeted for energy savings such as lighting, insulation of steam and chilled water networks, and leak reparation. In many cases, the company culture and employee engagement played an important role in energy reduction activities.

In the case collection conducted for this research, there is a good distribution of SMPs across the four A-labels (Table 4.3 and Table 4.4) showing that all types of modification are being used in industry: improvements can focus on the technology as well as on the resource flows; and both improved usage of resource or existing processes and substitution of resource or technology are widely used. It is important to note that the most common type of improvement is *Manage Equipment* which means that improved environmental performance could be achieved without significantly changing the manufacturing processes, e.g. without replacing equipment.

In the practice database, most SMPs collected are energy efficiency improvements through improved equipment use as opposed to technology substitution (Table 4.3). Then material efficiency mainly through resource substitution and wastewater treatment and reuse are the most common practices, followed by emission reduction through substitution practices and waste reduction through waste management practices. Finally, some cases focused on water use reduction which are often connected to wastewater treatment and reuse practices.

Looking at the responsibility of implementation (C-labels), most SMPs are associated with manufacturing process engineering and facility management. These improvements are mainly energy reduction practices through improved process management or equipment substitution (Table 4.4 and Table 4.5). Then operations management and manufacturing system engineering were both focused primarily on technology improvements.

Table 4.3. Practice database: A- and B-labels

		Manage Resource A1	Change Resource A2	Manage Technology A3	Change Technology A4	TOTAL
Energy	**B1**	130	90	324	219	**523**
Air emissions	**B2**	32	51	20	52	**109**
Water	**B3**	41	24	31	31	**76**
Wastewater	**B4**	105	72	15	65	**162**
Material	**B5**	73	99	39	60	**179**
Solid waste	**B6**	81	64	16	30	**112**
	TOTAL	**370**	**291**	**411**	**370**	

Table 4.4. Practice database: A- and C-labels

		Manage Resource A1	Change Resource A2	Manage Technology A3	Change Technology A4	TOTAL
Product / Product Designer	**C1**	3	10		4	**12**
Building design / Architect	**C2**	1			5	**5**
Facility Equipment / Facility Manager	**C3**	105	107	67	160	**263**
Manuf. Equipm. Change / Manuf. Systems Engineer	**C4**	30	29	42	139	**151**
Manuf. Process / Plant Manuf. Engineer	**C5**	123	83	188	137	**337**
Manuf. Equipm. Mngt / Operations Manager	**C6**	32	23	88	89	**155**
Equipment Maintenance / Plant Maintenance	**C7**	3	2	107	3	**111**
Equipment Operations / Shop Floor Staff	**C8**	32	27	5	7	**36**
	TOTAL	**370**	**291**	**411**	**370**	

Table 4.5. Practice database: B- and C-labels

		Energy B1	Air emissions B2	Water B3	Waste-water B4	Material B5	Solid waste B6	TOTAL
Product / Product Designer	C1	1	1			10	4	**12**
Building design / Architect	C2	3		1	1	1	1	**5**
Facility Equipment / Facility Manager	C3	203	16	22	32	29	13	**263**
Manuf. Equipm. Change / Manuf. Systems Engineer	C4	128	9	14	12	11	8	**151**
Manuf. Process / Plant Manuf. Engineer	C5	246	14	24	22	41	38	**337**
Manuf. Equipm. Mngt / Operations Manager	C6	115	10	13	12	22	8	**155**
Equipment Maintenance / Plant Maintenance	C7	90	4	9	3	10	4	**111**
Equipment Operations / Shop Floor Staff	C8	6	1		4	12	22	**36**
	TOTAL	**523**	**109**	**76**	**162**	**179**	**112**	

4.5 Chapter Summary

Extensive literature can be found on conceptual models and means of change with a particular focus on product design, end-of-life management, technological change, life cycle and supply chain management (as discussed in the literature review, Chapter 3). Despite the growth in sustainable manufacturing research as well as in industrial practice, it is still difficult to find information on how to improve manufacturing operations and resource flows from a manufacturer’s perspective. Moreover, cases available report only success stories with no cases of failure and little information about difficulties encountered or barriers to implementation (Despeisse et al., 2011). The absence of what the drivers and mechanisms are to implement SMPs can only hinder the wider adoption of the improvements achieved by manufacturers.

The available practices show that it is possible to improve the sustainability performance of manufacturing activities through practical measures to enhance the resource productivity. Efficient and effective material and energy use can reduce natural resource inputs and waste or pollutant outputs by keeping activities of the technosphere separate from ecosphere to avoid environmental degradation. Current research in the areas of manufacturing technologies and systems analysis are increasingly linked to resource productivity (mostly energy efficiency) and environmental assessment in addition to classic economic considerations.

In this chapter numerous cases of sustainable manufacturing were collected. The purpose of this case collection was to understand how companies are identifying improvement opportunities. SMPs were collected from two types of sources:

- Research papers with strategies, principles and approaches for sustainable manufacturing, sometimes based on a survey of industrial practices, or on analysis of current practices. These sources provided a wide range of practices but few details on the application of the practice or on the technical content of the activities.

- Internet website on best practices, examples from companies. These sources provided quantitative information on the activities and the results from the implementation, but few details on the difficulties encountered and how improvements were identified.

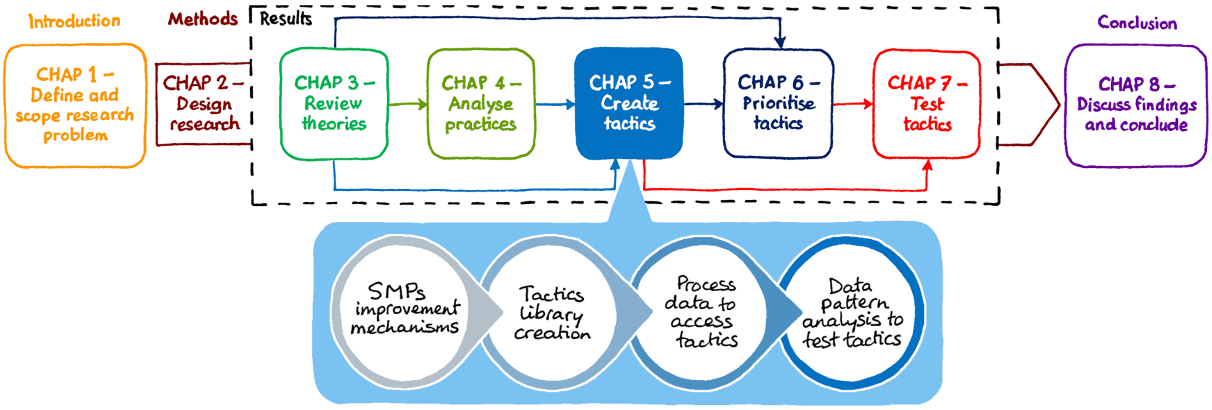
Most cases focused on the benefits of implementation rather than on the mechanism to identify improvements. However, the benefits reported can be used to trace back the means by which the improvements were achieved. Individual practices were then categorised according to three different labels. The first categorisation (A-labels) is based on the type of modification—organisational or operational *Manage* vs. technical or physical *Change*—and the elements targeted—*Resource Flow* vs. *Technology*. The second categorisation (B-labels) distinguishes the nature of the resource flow affected by the practices (inputs: energy, water, material; or outputs: air emissions, wastewater, solid waste) and allows to filter practices based the flow type and targeted benefits (energy reduction, CO_2 emissions abatement, water conservation, toxicity, "zero waste", etc.). Finally, the third categorisation (C-labels) identifies the functional responsibility to implement the improvements in the factory. Similarly to the second categorisation, it is used to narrow down the search of practices to specific functional areas of the company according to the responsibility of the people involved in the improvement activities.

The SMPs analysis revealed that a third of all SMPs collected included technological and resource change (substitution strategies) while the majority of SMPs focused on improving the use of existing equipment. This observation shows the role of green technologies and renewable resources but, even more importantly, the role of improved process management in sustainable manufacturing.

Chapter 5 TACTICS LIBRARY

Part of this chapter has been submitted in **Despeisse, M., Oates, M.R. & Ball, P.D., "Sustainable manufacturing tactics and cross-functional factory modelling",** ***J. of Cleaner Production*** **[In Press, Accepted Manuscript, Available online 15 November 2012]. DOI: 10.1016/j.jclepro.2012.11.008** of which the thesis author was the main contributor.

The previous two chapters presented the theoretical and practical aspects of sustainable manufacturing and showed that strategic models can be difficult to translate into operational activities. This chapter introduces the library of tactics which are generic formulations that extract the mechanism behind the practices to allow improvement opportunities to be identified. Access to tactics (through data pattern analysis and logic tests) is also introduced as the tactics library is integrated into the improvement methodology to enable the use of tactics through factory modelling.



5.1 Introduction

5.1.1 Focus of this chapter

This research focuses on sustainability in manufacturing as it has a major role to play in moving society towards more resource-efficient industrial systems. Although there are concepts for sustainability applicable to manufacturing (Robèrt, 1996; Lovins et al., 1999) and numerous examples of SMPs (Clelland et al., 2000; Fowler and Hope, 2007; Hesselbach et al., 2008; Ameling et al., 2010; Compressed Air Challenge, 2011; Bunse et al., 2011), there is a lack of information on how to move from these high-level sustainability concepts to the selection of appropriate practices. These examples of successful SMPs in various industrial sectors demonstrate that there are benefits in implementing sustainability improvements (Rusinko, 2007; Menzel et al., 2010); but the adoption of sustainability practices is not systematic (Madsen and Ulhøi, 2003). The literature and the case studies fail to provide the means by which improvements can be identified for more sustainable manufacturing operations and resource flows from a manufacturer's perspective. Examples of good practice are largely context specific and relate to specific problem situations. Thus it is difficult to understand how such improvements can be reproduced by others.

Throughout the literature, the flows of resources in the form of material, energy, water and wastes (MEW) reoccur (Ball et al., 2009). The MEW resource flows must be interpreted in the widest forms to include not just primary material conversion but others inputs and wastes such as water, consumables and packaging. Using the manufacturing ecosystem model (Despeisse et al., 2012a), all the MEW flows through a manufacturing system are captured with a graphical representation. The tactics are created by extracting the mechanism behind the SMPs collected in literature and formulated so that they can be widely applied to multiple technologies and resources. It means that tactics must be generic to capture the principles of improvement, but sufficiently detailed to be adapted to the specificity of the system studied. In order to avoid ambiguous formulations and misinterpretation, the tactics adopt a manufacturing language giving actionable guidelines for improving resource efficiency.

5.1.2 Objectives and deliverables

The aim of this research is to generalise SMPs by capturing the mechanism of change observed in industrial cases. While the literature proposed various approaches for sustainability, there is little guidance for manufacturing companies to identify sustainable improvements. This paper proposes a tactics library developed from a manufacturer’s perspective to support the generalisation of SMPs. The findings are considered to be novel in that the tactics are a set of tangible guidelines to operationalise sustainability in manufacturing systems through improved resource efficiency which is absent from the literature. The library of 20 tactics was formulated from hundreds of good practice examples. The tactics correspond to technical measures to improve resource efficiency in the factory.

The objectives of this chapter are: (1) to analyse the sustainable manufacturing practices collected (Chapter 4) by using a manufacturing ecosystem model (graphical representation); (2) to identify the improvement mechanisms in the SMPs and to identify patterns in the improvement mechanisms observed; (3) to formulate generic tactics based on each improvement mechanism and (4) to build the library of tactics.

5.2 Tactics Design

As mentioned in Chapter 4, the SMPs analysis was conducted in three phases: (1) the original collection of 210 practices resulted in the A-, B- and C-labels for categorising practices and developing the initial theory based on patterns observed; (2) more cases were collected by a third party to reach a total of 650 practices in a second phase which allowed to check the completeness and improve the structure of the tactics library; (3) finally, a third collection phase was conducted to reach a total of 967 SMPs and, as no further tactics were identified, to form the final tactics library.

Figure 5.1 shows the main steps in designing the tactics:

- The collection of SMPs presented in Chapter 4 was used as the basis for creating the tactics library. The SMPs are too specific to be reproduced by others and thus are difficult to generalise. Therefore, a pattern analysis was conducted to identify the replication logic of the data (SMPs). The practices were analysed through the lens of a visual representation to understand how the improvements modified the manufacturing system: by comparing a simplified system representation (models) before and after improvement, the patterns emerged.
- From the patterns observed in the data, improvement mechanisms were created to translate patterns into language. But the improvement mechanisms are the raw outcome of the pattern analysis and are not directly usable by manufacturers to identify improvements. Therefore, improvement mechanisms needed to be further refined into tactics to match manufacturing language and allow the user to make sense of them and implement them.
- The improvement mechanisms were also categorised according to the A-labels to identify missing mechanisms and thus missing tactics (i.e. check completeness and consistency). Further case collection was conducted as some tactics were not covered

by the initial practice database. It helped refine the content and structure of the tactics library. The final version of the tactics library was obtained after this second case collection as a third case collection was later conducted but did not result in new findings.

The following sub-sections describe in more details the identification of improvement mechanisms and the formulation of tactics.

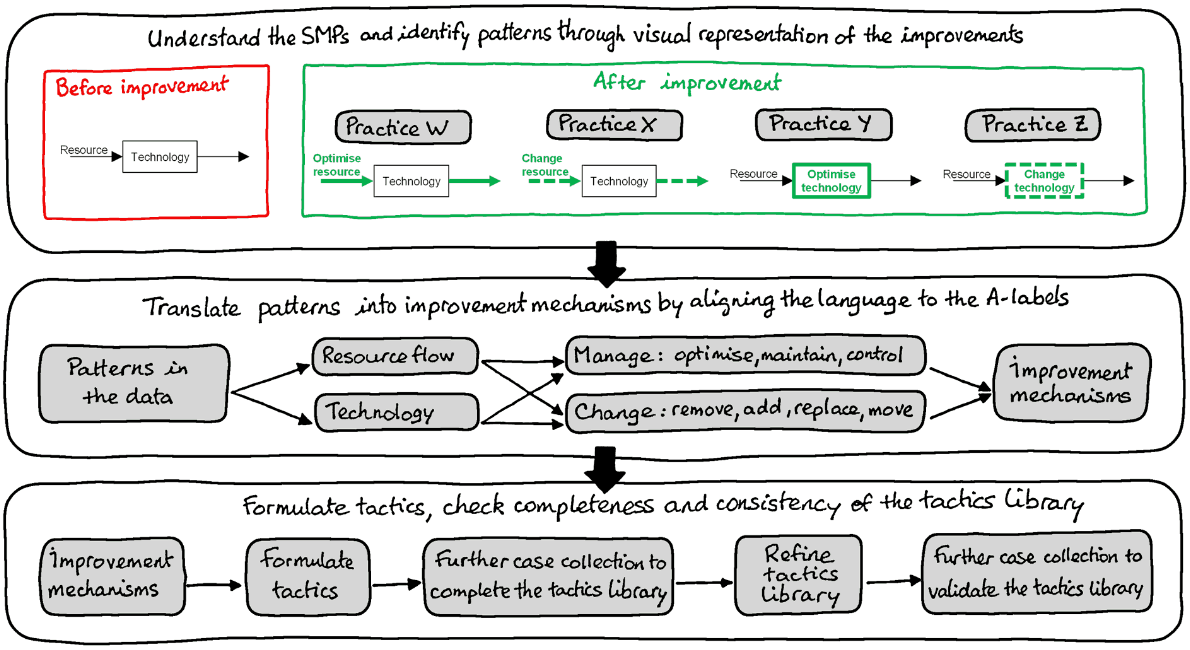


Figure 5.1. Tactics design: data patterns, improvement mechanisms and tactics library

5.2.1 *Improvement mechanisms*

The work focuses on practices that improve the sustainability performance of manufacturing activities. The work takes a gate-to-gate perspective (on-site activities only) to better understand resource (material, energy, water and waste – MEW) process flows from a systems viewpoint. The case study collection showed that there are numerous reported cases of SMPs across various industrial sectors. While these cases report what was achieved, few provide details on how these improvements were achieved. Analysis of the SMPs against main themes in sustainable manufacturing strategies resulted in the creations of a best practice database. The aim of the case collection was to identify the improvement mechanisms of the SMPs and generalise them, i.e. identify the generic rules for sustainable manufacturing.

Using the practices description, a model representation of the system before and after improvement can be deduced. Each type of modification made to this representation (or simplified model) correspond an improvement mechanism. Similar SMPs were grouped based on these mechanisms which are closely linked to the A-labels. Table 5.1 is an extract of the SMP database to show examples of practices with the corresponding improvement mechanism (and *tactic number* from Table 5.3 in next section).

Table 5.1. Extract of SMPs collection with the improvement mechanisms and tactics

#	SMPs	Improvement mechanism	A1	A2	A3	A4	Tactic	References
159	Development of low production new products: low weights, high grade non wooden products	Replace technology		✓		✓	A44	Conference paper (Ping and Yonghong, 2001)
160	Feedstock substitution (fibre regeneration, energy reuse, high-grade non-wood feedstock base building)	Change waste into resource flow	✓	✓			A24	
195	Good housekeeping	Maintain technology			✓		A31	Journal paper (Stoop, 2003)
196	Waste treatment	Maintain value of resource flow	✓				A15	
197	Rethink process layout (all wet processes located at one location)	Move technology			✓	✓	A45	
198	Reuse wastewater	Change waste into resource flow	✓	✓			A24	
203	More efficient technology to reduce the total basic power consumption	Replace technology				✓	A42	Conference paper (Herrmann et al., 2008)
204	Reduce energy consumption during non-production time by organizational and technical measures (stand-by-mode)	Optimise timing of resource flow	✓		✓		A11	
207	Alternative solutions, fluids with minimum environmental impact	Replace resource flow		✓			A22	
209	Extractive oil removal	Maintain value of resource flow	✓				A15	

Table 5.1. Extract of SMPs collection with the improvement mechanisms and tactics (cont.)

#	SMPs	Improvement mechanism	A1	A2	A3	A4	Tactic	References
308	Heat Distribution: Replace steam traps/drains with more efficient designs.	Replace technology				✓	A42	Environmental organisation website (Intelligent Energy – Europe (IEE), 2007)
314	Redesign system to minimise pipe runs.	Move resource flow	✓	✓			A25	
326	Space heating: Use heat only when area is occupied	Optimise timing of resource flow	✓				A11	
327	Set thermostats to minimum for comfort	Optimise efficiency of technology			✓		A32	
328	Minimise loss of hot air	Maintain technology			✓		A31	
332	Vent air from hot water systems	Change waste into resource flow	✓	✓			A24	
333	Time switches and manual controls	Control and monitor technology			✓	✓	A35	
338	Change energy source	Replace resource flow		✓			A22	
349	Compressed air: Install valves on air supply lines to individual machines.	Add technology				✓	A43	
350	Switch off compressed air supply as soon as machine off.	Optimise use of technology			✓		A33	
354	Fit 2-speed motors.	Add technology				✓	A43	
355	Fix leaks	Maintain technology			✓		A31	
356	Check on correct pressure setting regularly.	Control and monitor technology			✓		A34	
372	Refrigeration: Group refrigeration cells according to temperature.	Move technology			✓	✓	A45	
380	Monitor timing and duration of defrost cycles.	Control and monitor technology			✓		A34	
383	Switch off evaporator fans when compressor is off	Optimise use of technology			✓		A33	
384	Regulate condenser pressure (and therefore temperature)	Optimise efficiency of technology			✓		A32	
385	Delay start-up of compressors after start-up of ventilation.	Optimise magnitude of resource flow	✓		✓		A13	

Table 5.1. Extract of SMPs collection with the improvement mechanisms and tactics (cont.)

#	SMPs	Improvement mechanism	A1	A2	A3	A4	Tactic	References
563	Exchangers were redesigned to give more heat transfer overall.	Replace technology				✓	A42	Environmental organisation website (Energy Efficiency and Renewable Energy (EERE), 2001)
564	Introduce heat exchanger	Add technology				✓	A43	
565	Use a single incinerator instead of two	Remove technology				✓	A41	
566	Run distillation tower part-time to use lower-pressure steam when possible	Optimise magnitude of resource flow	✓		✓		A13	
571	Shutting down outmoded process systems	Remove technology				✓	A41	
654	Reuse of the cleanest part of the rinsing water	Change waste into resource flow	✓	✓			A24	Environmental organisation website (Danish Environmental Protection Agency, 2002)
656	Collection and reuse of printing paste that is left over after printing	Change waste into resource flow	✓	✓			A24	
657	Change from overflow rinsing to stepwise rinsing	Replace technology				✓	A42	
661	Chemical-free high speed rinsing after reactive dyeing of cotton	Remove resource flow		✓		✓	A21	
665	Collection and reuse of after treatment chemicals in finishing	Change waste into resource flow	✓	✓			A24	
956	Filtration of dye bath wastewater	Maintain value of resource flow	✓				A15	Environmental org. website (NCDENR, 1995)
957	Recycle and reuse of water	Change waste into resource flow	✓	✓			A24	

The improvement mechanisms listed in Table 5.2 were identified by comparing the initial system (where the inefficiency is) and the improved system (what solution was implemented). In many cases, the solution appears obvious once the inefficiency is identified, such as leaks to be repaired or unused equipment to switch off. Therefore the most important step is to identify the inefficiency. The question to answer is "what are the symptoms of inefficiency?" The cases did not explain how particular inefficiencies were identified and how solutions were found.

Table 5.2. Improvement mechanisms and A-labels

	Resource	**Technology**
Manage	**A1 Manage Resource** Optimise timing or magnitude of resource flow Maintain value of resource flow	**A3 Manage Technology** Optimise timing or magnitude of demand or supply of technology component Maintain performance of technology component Control and monitor performance of technology component
Change	**A2 Change Resource** Change (add, replace or remove) resource flow Change waste into resource flow Move resource flow	**A4 Change Technology** Change (add, replace or remove) technology component Move technology component

The main mechanisms under *A1 Manage Resource* link to the timing and magnitude of resource flows: by optimising inputs and outputs and recognising the value of waste flows, the resource flows could be better managed and overall efficiency improved. Under *A3 Manage Technology* the mechanisms of improvement mainly correspond to modifications in process controls or set points and to adjustment in demand and supply between processes. Finally, under *A2 Change Resource* and *A4 Change Technology*, the main mechanisms of improvement correspond to physical alterations to the infrastructure such replacing inefficient equipment, adding new process technology, introducing renewable or more efficient resources, and changing pipelines location to reduce losses in supply networks.

5.2.2 Tactics formulation

Similar SMPs were grouped based on the improvement mechanism identified (Table 5.2) and each mechanism was translated into a *generic tactic*. But before tactics could be formulated, a systematic approach to the improvement mechanisms was needed. This was achieved by analysing the SMPs through the lens of a visual representation of the system (as introduced with the A-labels in Figure 4.1) before and after improvement. Similar patterns of improvement could be identified in the SMPs and were listed as the main mechanisms of change for sustainable manufacturing. With the aim of generalising good practices for sustainable manufacturing, each mechanism of change was formulated into a generic tactic. Table 5.3 shows the complete library of tactics.

To demonstrate how improvement mechanisms were identified and how tactics were formulated, two examples are presented in this section: diagramming technique as illustrated in Figure 5.2 (TECHNOLOGY represented as boxes and RESOURCE represented as arrows) and data plots as illustrated in Figure 5.3 (process data as "profiles", i.e. flow magnitude vs. time).

Table 5.3. Tactics library structured according to A-labels

	Resource	Technology
Manage	**A1 Manage Resource** A11 Align resource input profile with production schedule A12 Optimise production schedule to improve efficiency A13 Optimise resource input profile to improve efficiency A14 Synchronise waste generation and resource demand to allow reuse A15 Waste collection, sorting, recovery and treatment	**A3 Manage Technology** A31 Repair and maintain A32 Change set points/running load, reduce demand A33 Switch off/standby mode when not in use A34 Monitor performance A35 Control performance
Change	**A2 Change Resource** A21 Remove unnecessary resource usage A22 Replace resource input for better one A23 Add high efficiency resource A24 Reuse waste output as resource input A25 Change resource flow layout	**A4 Change Technology** A41 Remove unnecessary technology A42 Replace technology for better one A43 Add high efficiency technology A44 Change the way the function is accomplished A45 Change technology layout

Example 1 is shown in Figure 5.2. It illustrates a cutting process, filtering of the cutting fluid and swarf, and separate cleaning processes for the product and the swarf. Tactic A41 suggests eliminating the filtering of the cutting fluid to separate it from the swarf. Tactic A21 suggests eliminating water usage to clean the swarf as the cutting fluid can be separated from the swarf by using gravity: the cutting fluid accumulates at the bottom of the skip over time and can be recovered through an evacuation system at the bottom. Tactic A21 also suggests eliminating the use of a detergent in the cleaning process as it does not affect the quality of the final product (water rinse being sufficient). Tactic A22 suggests that the cutting fluid could be replaced by a reusable one. Tactic A42 suggests that the cutting process technology could be replaced by a more efficient one. Finally tactic A24 suggests the cleaning water and recovered cutting fluid could be reused.

Example 2 is illustrated in Figure 5.3. The product profile (green in Figure 5.3 corresponds to the production volume variation over time for a given process. This product profile dictates the minimum demand which must be fulfilled by the supply. An example could be a cleaning process where the supply profile corresponds to the energy used to heat up and pump water. It initially consumes a fixed amount of energy as the process is constantly running full load (red line in Figure 5.3). Tactic A11 suggests that there should be no resource input (energy and hot water) when there is no product being processed. Tactic A33 suggests putting the process in stand-by mode between two batches if switching on and off would consume more energy (minimum energy required to keep the water at the temperature set point vs. energy required to heat the water back up to set point). Tactic A31 suggests reducing losses through repair and maintenance (check proper insulation of hot water tank). Tactic A32 suggests challenging the set point (minimum temperature to achieve the required quality of product output). And finally tactic A35 suggests installing a controller on the pump so that the hot water supply level matches the minimum requirement for cleaning products resulting in the final supply profile (in blue in Figure 5.3).

As tactics are generic, each can cover various technological solutions and resource flows. In other words, each tactic can generalise the practices used to formulate it to other types of resources and technology (equipment or processes). For instance the tactic *A32 Change set points/running load, reduce demand* can correspond to various practices such as *Set thermostats to minimum for comfort* for space heating (practice 327) or *Regulate condenser pressure* for a refrigeration process (practice 384). Thus the total number of tactics formulated was as low as the 20 tactics for covering a wide range of practices from various manufacturing sectors.

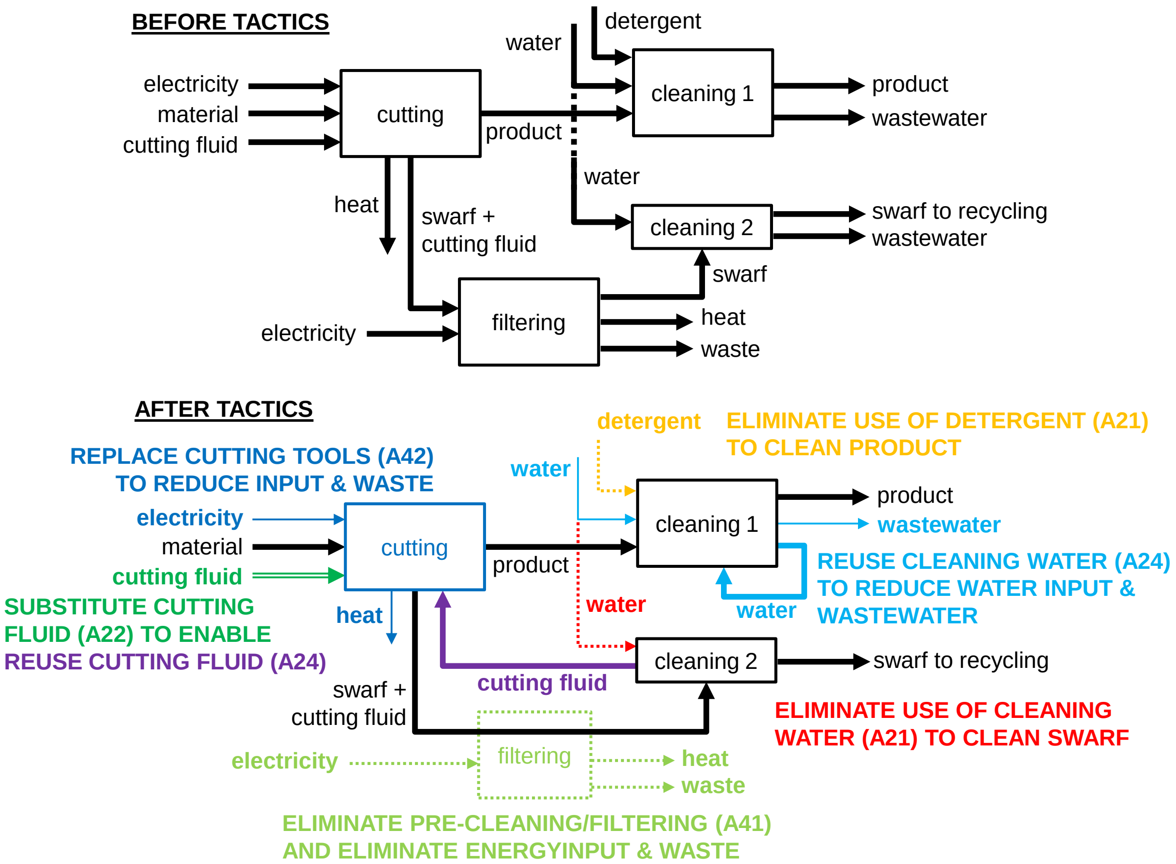


Figure 5.2. Schematics showing improvement practices and corresponding tactics

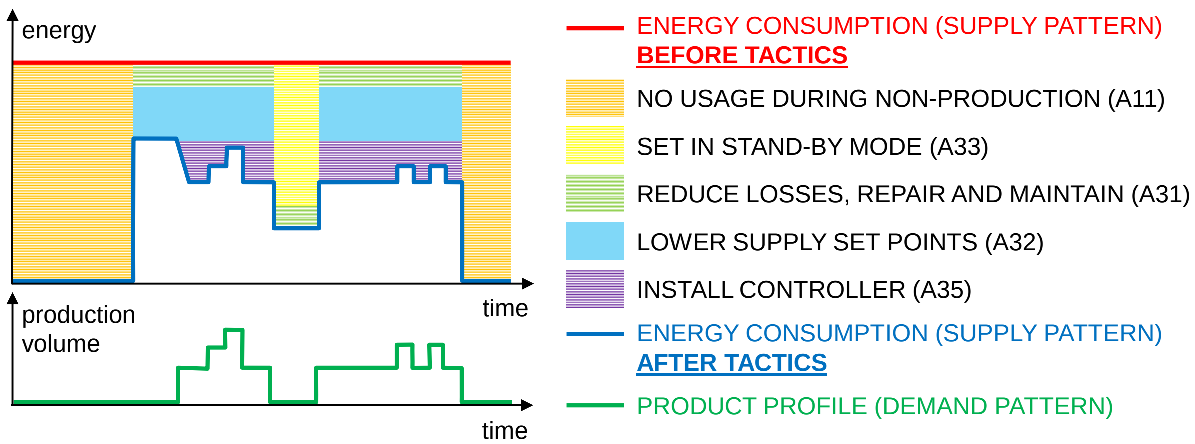


Figure 5.3. Process data profiles showing improvement practices and corresponding tactics
Energy profile (supply pattern) before tactics implementation (in red)
and after tactics implementation (in blue)

Conversely, it is important to note that certain practices from Table 5.1 potentially fit under multiple tactics since they can belong to different types of modification at the same time. For instance, practice 203 in Table 5.1 can correspond to two tactics: *"More efficient technology to reduce the total basic power consumption"* can be both *A42 Replace technology for better one* and *A32 Change set points/running load, reduce demand*. Tactic A42 was considered as the closest to the improvement activity while A32 was considered as the consequence of implementing it. Therefore, practice 203 was labelled as an A42 tactic.

The categorisation of tactics under the A-labels can also present difficulties: for instance, *A21 Remove unnecessary resource flow* is categorised under A2 Change Resource although it might require changing the process using this resource (thus also corresponds to A4 Change Technology), or *A13 Optimise resource input profile to improve efficiency* (A1 Manage Resource) which is done to improve equipment efficiency (thus also corresponds to A3 Manage Technology).

The researcher chose to categorise such improvement mechanisms under the most appropriate A-label based on her interpretation of how the model modification would function in a modelling tool. For instance, although the tactic *A24 Reuse waste as resource* implies a good waste management (A1 Manage Resource), it has been categorised under A2 Change Resource since it would mean replacing part of the virgin resource flow by a recycled waste flow. Another example is *A45 Change technology layout* which implies improved usage of existing technology (A3 Manage Technology) but has been categorised under A4 Change Technology as the model would be changed by removing the technology component from one factory zone and adding it in another.

Finally, there are also practices which did not match any tactic as they correspond to behavioural measures. For instance a practice such as *"Set up individual responsibilities to operators for shut-off practices"* is a behavioural measure which would result in the activity of switching off unused equipment. Therefore this practice can be included in the SMP collection and labelled *A33 Switch off/standby mode when not in use*. A second example is *"Protect personnel/equipment"* which does not correspond to any tactic and therefore cannot be labelled. Such practices were kept in the SMP database as they are still relevant and could be used as a "tip" or "advice" to manufacturers.

5.3 Tactics Access

Tactics can be accessed through tests performed on process data (metered data, equipment specification and resource characteristics). The following two subsections show how tactics are tested to identify improvement opportunities.

5.3.1 Process data

Process data are needed to characterise the elements of the system under study. The three main subsystems considered in the process data analysis are:

- Manufacturing operations: manufacturing process systems (boundaries and connections), associated equipment (links to process systems), material flows (added value product, non-value added waste, and process system flow paths);
- Supporting facilities: facility equipment, inputs to manufacturing operations (e.g. compressed air, steam, cooling water), outputs (e.g. exhaust fumes, waste heat);
- Surrounding buildings: building geometry, construction data, weather data, HVAC systems and internal gains.

The MEW flows within and between these three sub-systems are crossing functional boundaries and therefore promote an ecosystem view of the factory (Despeisse et al., 2012a). Therefore the elements modelled are the buildings, the technology components (equipment and processes) placed in and near the buildings, and the resource flows linking all elements of the model (inputs: energy and material including water and chemical; outputs: product and wastes including physical waste accumulating in bins as well as energy waste mostly in the form of heat). All elements of the system are characterised by process data and can also be linked to best practices through the B-labels see (section 4.3.2).

Table 5.4 shows the list of process data and the corresponding real-world information collected by the user (right-hand column). Each type of process data is associated with a reference number in squared brackets to help better understand the logic tests and pattern analysis used to access tactics.

Some of the process data and profiles can be defined as constraints to determine the minimum requirements (inputs quantity and quality) for the manufacturing processes to achieve their function correctly (product output quantity and quality): mainly production schedule and set points. The other process data and profiles can be functions of these constraints or metered data. Other variables must be defined to characterise the technology elements (equipment and processes, or the transformation processes): capacity or equipment rating, running load (including the minimum/base load and maximum/peak load), the performance/efficiency curve (ratio output/input as function of running load), etc. Other optional information can be added to increase the quality of the analysis, such as equipment age (depreciation time), operating cost, etc.

Data collection of actual inputs, outputs including emissions and waste streams can be challenging and costly. The amount of efforts place in collecting data must be balanced with the desired level of analysis (i.e. coarse vs. detailed) and the ensuing quality of the results. Thus it is important to carefully consider what the appropriate level of data granularity is so that only data sufficient for analysis is collected (as opposed to detailed data required by default before starting the analysis). This granularity issue can affect the level at which the data is metered as well as the time interval between two values and the magnitude of the flow to be taken into account. It is common that the level of granularity of data varies for different resource types. For instance, the consumption of different types of resources could be metered at different levels: the total resource use (water, gas, electricity, chemicals, etc.) of a manufacturing plant may be known based on the consumption bills, but only gas and electricity is metered inside the manufacturing system. Additionally electricity could be metered at a more detailed level than gas due to the facility network structure and more advanced metering equipment.

5.3.2 Logic tests

Each tactic can be accessed through logic tests (pattern analysis), simulation or qualitative advice to user (tips using the SMPs database). The main mechanisms of improvement identified during the SMP analysis were used to understand which process data needed to be tested to identify the improvement opportunity.

Table 5.5 shows the list of tests corresponding to each tactic. Some of the process data listed in Table 5.4 are not used to test for tactics but are needed to create a meaningful model, e.g. construction data [2] to determine the thermal performance of the building and technology component geometry [4] to represent the component in the model.

This list of process data differentiate inputs and outputs so that they can be used to create a chain of constraints. E.g. the set points [11] and product profile [10] establish the minimum requirements for a given process, which determines the appropriate control profile [12] and level of input [13] required for this process, and consequently the corresponding minimum utility supply [14] from the facility equipment, which in turn determine the minimum primary resource supply [11] for this facility equipment.

Table 5.4. List of process data for modelling and the corresponding data sources

Process data (model)	Data source (real-world)
***Building model**: Drawing the infrastructure*	
[1] Building geometry/thermal zones	Factory layout (technical drawings)
[2] Construction data	Building construction materials
[3] HVAC systems	Building Service System documentation
***Qualitative process model**: Mapping manufacturing operations & facilities*	
[4] Technology component geometry	Equipment/processes dimensions (optional)
[5] Technology component layout	Equipment/processes location (technical drawings)
[6] Technology component attributes/characteristics	Equipment/process specifications
[7] Resource flow layout	Energy and material path/network layout
[8] Resource flow characteristics	Energy and material characteristics
[9] List of processes (qualitative product flow)	Manufacturing routings
***Quantitative process model**: Modelling manufacturing operations & facilities*	
[10] Production profile (factory-wide), equipment/process operations profile, product profile (quantitative product flow)	Production schedules
[11] Technology component set point/demand profiles	Process set points/running load
[12] Technology component control profiles	Controls (controllers, valves, etc.)
[13] Resource input/usage profiles	Resource consumption (metered data)
[14] Resource output/supply profiles	Utility resource generation (metered data)
[15] Waste profiles	Waste generation
[16] Total inputs to the system (check completeness)	Total resource use (energy/water bills and BOM – bill of materials)
[17] Energy and mass balance (check missing data)	Thermodynamics for resource transformation process
[18] Link technology component to HVAC system	Thermal transfer to space/building
[19] Link technology component to bins (waste profile, energy and mass balance)	Waste data (if available)
***Optimised process model**: Improvements implementation*	
[20] Controller functions (for simulation purpose)	Control strategy
[21] Bins/recycling repositories	Recover, sort, collect, reuse, recycle
[22] Modification to technology component	Equipment/process management or change
[23] Modification to resource flow	Resource management or change

Table 5.5. Logic tests and access to tactics through process data

Tactics and logic tests
A1 Manage resource
A11 Align resource input profile with production schedule
Look for mismatch between product profile [10] and usage [13]/supply [14]
A12 Optimise production schedule to improve efficiency
Simulate shift in product profile [10] to improve efficiency *
A13 Optimise resource input profile to improve efficiency
Simulate shift in demand [11]/usage [13]/supply [14] profile to improve efficiency *
A14 Synchronise waste generation and resource demand to allow reuse
Adjust demand [11]/usage [13] and waste [15][17][19][21]
A15 Waste collection, sorting, recovery and treatment
Look for significant waste output [15][17][19][21] and/or [8] (quantity/toxicity)
A2 Change resource
A21 Remove unnecessary resource usage
Look for Best Practices based on RF types [8] **
A22 Replace resource input for better one
Look for environmental alternative to black listed RF attributes [8][22] **
Look for Best Practices based on RF attributes [8][22] **
A23 Add high efficiency resource
Look for Best Practices linked to RF types [8][22] **
A24 Reuse waste output as resource input
Look for matching RF attributes [8]/demand [11]/usage [13] and waste [15][17][19][21]
A25 Change resource flow layout
Look for mismatch between thermal zone [1]/HVAC system [3] and RF layout [7]/attributes [8]
A3 Manage Technology
A31 Repair and maintain
Look for incomplete energy/mass balance between [17] data points, or total inputs [16]
A32 Change set points/running load, reduce demand
Simulate change in set point [11]/control [12][20] to improve efficiency *
A33 Switch off/standby mode when not in use
Look for mismatch between product profile [10] and demand [11]/control [12][20]
A34 Monitor performance
Create a new set point [11]/control [12][20]/usage [13]/supply [14]
A35 Control performance
Adjust set point [11]/control [12][20]/usage [13]/supply [14] based on simulation results *
A4 Change Technology
A41 Remove unnecessary technology
Look for Best Practices linked to TC types [6] **
A42 Replace technology for better one
Look for Best Practices based on TC characteristics [6][22] **
Look for environmental alternative to black listed TC characteristics [6][22] **
A43 Add high efficiency technology
Look for Best Practices linked to TC types [6][22] **
A44 Change the way the function is accomplished
Look for possibilities to use Best Practices based on TC functions [6][22] **
A45 Change technology layout
Look for mismatch between thermal zone [1]/HVAC system [3][18] and TC layout [5]/attributes [6]

RF = resource flow; TC = technology component (equipment or process);
** use simulation; ** use practice database.*

5.4 Chapter Summary

In this chapter, the gap between sustainability concepts (Chapter 3) and industrial practices (Chapter 4) has been examined to extract the mechanisms behind the improvements achieved and formulate generic tactics for resource efficiency (which provide information on how improvements can be implemented). Tactics are verb–noun formulations to specify the type of change (remove, replace, add, optimise, etc.) and the focus of the change (resource flow or technology component). Tactics are thus both generic enough to be applicable in multiple environments, but are also specific enough to be actionable in those environments and disciplines leading to specific process-level improvements.

This research focuses on measures taken in the factory and therefore adopts a gate-to-gate perspective for manufacturing system analysis. To achieve sustainable industrial systems and sustainability at societal level, a more holistic approach is needed. However, this study draws the boundaries of the systems studied around the elements on which manufacturers have full control. This in turn contributes to the overall industrial sustainability challenge by supporting the identification of improvements in resource efficiency at factory level, i.e. holistic solution when viewing the whole site, but local solution as focusing on a single site. Additionally the resource flows considered in this study are energy, material, water, chemicals, etc. and not capital, employees, etc. In other words, the study focuses on the physical resource flows.

The case analysis shows that there are patterns in the SMPs collected when analysed with visual representation methods (plot of process data as profiles or process and flow maps). Multiple practices for various technology and resource types could be represented with the same diagraming or profiling patterns and therefore correspond to a single tactic. As the aim of the study was to address the first research question about generalisation of SMPs, this was an expected finding. However some practices could also be represented in different ways depending on the process data considered or based on the granularity of data used to represent the same improvement. Therefore these practices could correspond to multiple tactics. In such cases, the tactic considered to be the closest to the activity resulting in the improvement reported in the case source would be chosen.

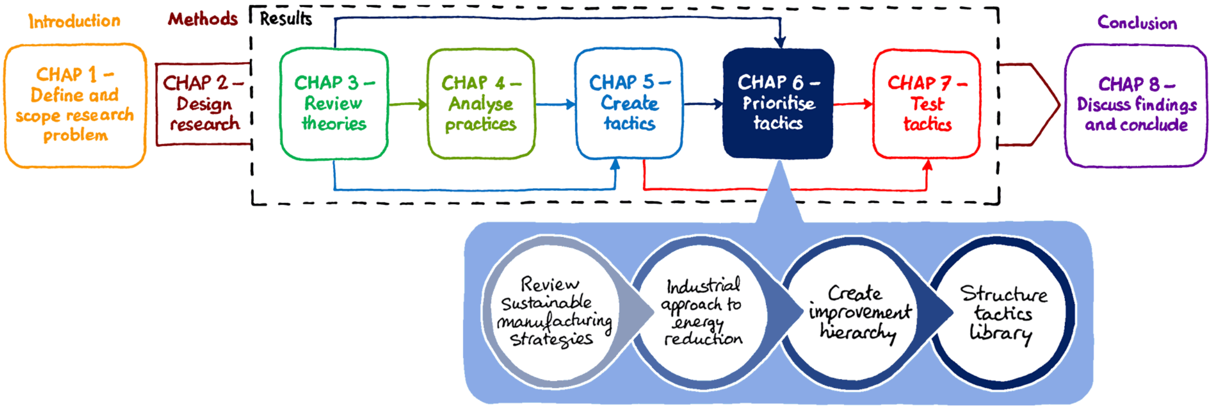
The tactics library design presented in this chapter demonstrates that it is possible to generalise SMPs through a limited number of tactics. The library of tactics covers 1000+ practices collected as well as a wide variety of concepts and strategies for sustainability applicable in manufacturing. The tactics consequently bridge the gap between sustainability concepts and practices by providing generic and tangible principles for applying sustainability in a factory through improved resource efficiency. Although limited to technical measures as tactics correspond to improvements which manufacturers can directly apply, the work shows that there are a few simple rules which can support the identification of SMPs. Tactics are thus both generic enough to be applicable in multiple environments, but also specific enough to be actionable in those environments and to lead to specific process-level improvements.

In order to implement the tactics, a methodology (or "user guide") is needed to structure the identification of inefficiencies and the selection of appropriate options by following the reasoning of the 'Rs' strategies (reduce first, then reuse if possible, and finally recycle). This in turn would support decision-making for sustainable manufacturing. The next chapter introduces such a methodology to guide manufacturers in approaching improvements for more sustainable operations.

Chapter 6 IMPROVEMENT HIERARCHY

Part of this chapter has been submitted in **Despeisse, M., Oates, M.R. & Ball, P.D., "Sustainable manufacturing tactics and cross-functional factory modelling",** ***J. of Cleaner Production*** **[In Press, Accepted Manuscript, Available online 15 November 2012]. DOI: 10.1016/j.jclepro.2012.11.008** of which the thesis author was the main contributor.

This chapter introduces an improvement hierarchy which is based on findings from the literature review and an industrial approach to energy reduction: the improvement hierarchy integrates the energy and waste hierarchies as well as various strategies and principles for sustainable manufacturing. This improvement hierarchy is then used to restructure the library of tactics by prioritising their implementation order.



6.1 Introduction

6.1.1 Focus of this chapter

Critical elements for sustainable manufacturing are the production system as well as the buildings and facilities which are servicing manufacturing operations and provide heating, ventilation, air-conditioning (HVAC), lighting, power, water, and waste removal. Driven by increasingly tighter building energy regulations and voluntary green rating systems, methodologies have been developed to guide design and reduce resource use, including modelling and simulation tools. However, buildings and manufacturing facilities are typically managed separately and use different performance metrics. Historically, buildings in many industrial situations have lifetime values that are low compared to the production process; as a result little emphasis has been placed on buildings. There is significant potential for resource efficiency improvement by integrating these disciplines and viewing the factory as an ecosystem (Despeisse et al., 2012a; Oates et al., 2011b).

Resource efficiency improvements in manufacturing can only take place through wide changes spanning from behavioural to technological changes, and through holistic perspective as well as local solutions. Additionally, sustainable manufacturing challenges involve rapid technological change, interconnected and complex problems. To tackle these problems, powerful IT tools have been developed to enable the analysis of ever more interconnected and complex systems. Various modelling and energy analysis tools have shown possible to provide tangible benefits towards sustainable manufacturing (Gutowski et al., 2009; Heilala et al., 2008; Michaloski et al., 2011; Herrmann and Thiede, 2009). However, while these tools are helpful to support improvements, they do not provide a practical approach and overall structural framework for the users across functions to identify inefficiencies or improvement options for resource efficiency. Manufacturers willing to embark on sustainable improvement activities need a structured approach to know where to start. Therefore, guidance is required on how to achieve sustainable improvement in manufacturing. In this chapter, the issues of *getting started* and improvement options prioritisation are addressed.

6.1.2 Objectives and deliverables

The review of the sustainable manufacturing literature (Chapter 3) highlighted the necessity and emergence of this relatively new field, and the ensuing main dimensions and concepts. As sustainability issues are gaining importance in corporate strategy, there is a need to understand how improvements can be achieved in manufacturing operations. The literature proposes lists of themes, conditions, principles and strategies for sustainability. Some of these strategies are presented in the form of ordered lists where options are ordered according to complexity and scope of improvement (Mohanty and Deshmukh, 1998; Abdul Rashid et al., 2008), or according to options' priority, e.g. some options should be prioritised over others as they have the most desirable outcomes (Sarkis and Rasheed, 1995; Sarkis, 1995). The later type of ordered list is called *hierarchy* in this research.

This chapter presents a synthesis of the findings from literature on sustainable manufacturing practices (SMPs) in the form of an improvement hierarchy. This improvement hierarchy replicates an existing industrial approach which has proven to be successful to reduce energy usage across various manufacturing processes. This industrial approach was developed by Toyota as *6 attitudes to energy reduction* (Hope, 2011). It is similar to the energy and waste hierarchies in that it proposes strategies for improvement with a prioritisation order, from the most desirable option to the least desirable. The improvement hierarchy is thus used to restructure the tactics library and prioritise tactics to support a methodical identification of improvement opportunities. This in turn addresses the second research question: the improvement hierarchy provides a structured and practical approach for manufacturers to undertake sustainable improvement activities in their factory.

6.2 Sustainable Manufacturing Strategies and Principles

Various authors have proposed sets of strategies or principles for industrial sustainability. Table 6.1 presents two types of sets of strategies and principles: certain authors are presenting conditions for sustainability which must all be fulfilled while others are presenting options with a most preferred one and a least preferred one. Despite this difference in approaches, Table 6.1 shows similar themes across the strategies or principles for tackling sustainability issues at different levels:

- At the source with preventive measures such as product and process design and dematerialisation to reduce the intake of resource in the technosphere.
- During manufacturing with technical and organisational measure to increase the efficiency with which resource are transformed into economically valuable goods.
- At the end of product life cycle with closed-loop circulation of resource within the technosphere through reuse, remanufacturing and recycling.

These three main themes were used as a foundation for creating the improvement hierarchy and more specific steps were defined by using the energy and waste hierarchies (Dovì et al., 2009; Sarkis and Rasheed, 1995; Lund, 2007; Blackstone, 2011). These hierarchies help to prioritise improvement options by identifying at which stage an improvement should be implemented. The material waste hierarchy is well-established and is typically represented by a pyramid with Reduce-Reuse-Recycle-Recover-Dispose, reduction being the first priority at the top, and dispose being the last option at the bottom. Analogous energy and low-carbon hierarchies also exist to prioritise improvements in energy use avoidance at the top, going down through the levels of technology for energy efficiency and shift to renewable energy sources, and finally at the bottom of the hierarchy, offsetting techniques and carbon sequestration considered as the last resort (London Energy Partnership, 2004; Hope, 2008). It is therefore appropriate to structure the library of tactics based on a similar improvement hierarchy for resource efficiency. It incorporates existing sets of strategies and principles for industrial sustainability (Allwood, 2005; Lovins et al., 1999; Abdul Rashid et al., 2008) in addition to the waste/energy hierarchies mentioned earlier.

The issue of "which improvement option comes first" can be debated as the hierarchies can be represented and interpreted differently: the waste and energy hierarchies are typically represented by a pyramid with the most desirable options (prevention) at the top and the least desirable at the bottom. In some cases, the hierarchy is represented by an inverted pyramid where the widest part at the top represents the starting point, i.e. the most desirable option.

Additionally, such representation can also be misinterpreted. One could view the least desirable options as the current situation (e.g. landfill and use of fossil fuels) and therefore the next step in the sequence would still be among the least desirable: from the bottom of the pyramid, one must move to the next level above which still has a low performance, and progressively move up the pyramid towards the most desirable options at the top. This misinterpretation has been addressed by the improvement hierarchy developed by the researcher; this issue of "what comes first" will be further discussed in section 6.4 as the improvement hierarchy is introduced.

Table 6.1. Strategies and principles for sustainable manufacturing in the literature

Reference	**Strategies or principles**
(Abdul Rashid et al., 2008) Sustainable manufacturing strategies	1. Waste minimisation 2. Material efficiency 3. Resource efficiency 4. Eco-efficiency
(Allwood, 2005) Options for sustainable manufacturing	o Use less material and energy o Substitute inputs: non-toxic for toxic, renewable for non-renewable o Reduce unwanted outputs: Cleaner production, Industrial symbiosis o Convert outputs to inputs: recycling and all its variants o Changed structures of ownership and production: product service systems, supply chain structure
Dornfeld (2009) Strategies for Green Manufacturing (adapted from Allwood, 2007)	o Invest in business intelligence/analytics o Redesign all scales of manufacturing flow o Shift to a service-oriented business o Use less material and energy o Substitute input materials o Reduce unwanted outputs o Convert outputs to inputs
(Gladwin et al., 1995) Sustainability principles and their operational principles	o Assimilation: Waste emissions ≤ Natural assimilative capacity o Regeneration: Renewable harvest rate ≤ Natural regeneration rate o Diversification: Biodiversity loss ≤ Biodiversity preservation o Restoration: Ecosystem damage ≤ Ecosystem rehabilitation o Conservation: Reduce energy-matter throughput per unit of output o Dissipation: Reduce energy-matter throughput o Perpetuation: Non-renewable resource depletion ≤ Renewable resource substitution o Circulation: Reduce virgin ÷ recycled material use

Table 6.1. Strategies and principles for sustainable manufacturing in the literature (cont.)

Reference	Strategies or principles
(Hibbard, 2009) Key steps in making manufacturing more sustainable	o Optimize use of fossil fuels o Eliminate waste o Reduce, eliminate pollution o Recycle o Recover energy o Save time
(Jawahir et al., 2005) Strategic technology areas of sustainability applications for products and processes	o Waste-free processes o New materials processes o Enterprise modelling and simulation o Improved design methodologies o Education and training
(Lovins et al., 1999) Major shifts for the journey to natural capitalism	o Dramatically increase the productivity of natural resources o Shift to biologically inspired production models o Move to a solutions-based business model o Reinvest in natural capital
(Mohanty and Deshmukh, 1998) Green productivity strategic choices	1. Waste reduction 2. Waste control 3. Waste avoidance 4. Waste prevention
(Rahimifard and Clegg, 2007) Main themes for design and manufacture	o Design for Environment o Supply Chain Management o End-of-Life Management
(Robèrt et al., 2002) Objectives to address the four system conditions of the natural step	o Eliminate our contribution to systematic increases in concentrations of substances from the Earth's crust: substitute scarce minerals with others more abundant, use all mined materials efficiently, reduce fossil fuel dependency. o Eliminate our contribution to systematic increases in concentrations of substances produced by society: substitute persistent and unnatural compounds with ones normally abundant or break down more easily in nature, use all substances produced by society efficiently. o Eliminate our contribution to the systematic physical degradation of nature: draw resources from well-managed eco-systems, pursue the most productive and efficient use both of those resources and land, exercise caution in all kinds of modification of nature. o Contribute to the meeting of human needs, using all of our resources efficiently, fairly and responsibly so that the needs of all people and the future needs of people stand the best chance of being met.
(Sarkis and Rasheed, 1995) Rs strategies	1. Reduce 2. Remanufacture 3. Recycle and Reuse
(Seliger et al., 2008) Strategies to enhance use-productivity	o Implementation of Innovative Technologies o Improving Use-Intensity o Extension of Product Life Span
(Westkämper et al., 2001) Processes in product life cycle towards sustainable manufacturing	o Engineering: analysis of technical functions o Manufacturing: optimization of processes and logistics o Use: technical behaviour and utilization rates

To summarise, sustainability requires improved resource use-productivity (Seliger et al., 2008; Seliger et al., 1997) in order to reduce natural resource inputs as well as consequent waste and pollutant outputs. SM activities follow sets of rules defined by various authors as they describe the major changes needed to move towards more sustainable industrial practices:

1) Use less - by dramatically increasing the productivity of natural resources (material and energy): technological progress in manufacturing (Seliger and Zettl, 2008; Thiede et al., 2011) and life cycle considerations in product design (Rahimifard and Clegg, 2007; Bhamra, 2004; Lakhani, 2007; Jawahir et al., 2007), managerial and technological practices to improve environmental performance across sectors (Goldstein et al., 2011);
2) Shift to biologically inspired production models - such as reduction of unwanted outputs and conversion of outputs to inputs: industrial symbiosis (Graedel and Howard-Grenville, 2005; Ehrenfeld and Gertler, 1997), product end-of-life management and all its variants including disassembly (Westkämper et al., 1999)and remanufacturing (Seliger et al., 2008);
3) Move to solution-based business models - including changed structures of ownership and production: supply chain structure (Srivastava, 2007; Beamon, 2008; Sarkis, 2003) and product-service systems (Mont, 2002) which "values asset performance or utilization [of a product] rather than ownership" (Baines et al., 2007);
4) Reinvest in natural capital - through substitution of input materials: toxic by non-toxic and non-renewable by renewable (Allwood, 2005; Lovins et al., 1999; Abdul Rashid et al., 2008).

6.3 Industrial Approach to Sustainability

A large number of companies are conducting sustainable manufacturing activities as demonstrated by the number of practices collected for this research. However the approach used by these companies is rarely documented. A few industrial approaches, such as the ones used by Ricoh and Toyota, have been widely publicized (Ricoh, 2011; Hope, 2011). The approach proposed by Ricoh encompasses a wider system (whole supply chain, user and waste handler) than the scope of this research (a manufacturing unit). The Toyota approach corresponds better to the scope of this research and thus was used as a model alongside the waste and energy hierarchies to develop the *improvement hierarchy*.

The Toyota's approach to energy reduction has allowed the company to achieve significant reduction in energy consumption over the past two decades (Evans et al., 2009). It is similar to the waste hierarchy discussed in the previous section as it prioritises improvement options: *reduce* first, then *reuse* when possible and finally *recycle*. The *Toyota's 6 attitudes* for energy saving are: *Stop*, *Eliminate*, *Repair*, *Reduce*, *Pick-up* and *Change*. These attitudes have also been adopted by Airbus and renamed to create the *StRe3TCh methodology*: *Stop*, *Remove**, *Repair*, *Reduce*, *Trade** and *Change* (* renamed steps compared to *Toyota attitudes*) (Lunt and Levers, 2011). The *Toyota's 6 attitudes* prioritise energy improvements based on the magnitude and complexity of change as well as on the difficulty of implementation in terms of effort and financial investment.

Toyota applies these attitudes for energy reduction in 3 stages. The first stage reduces energy consumption during non-production periods with *Stop* and *Eliminate* attitudes. The *Stop* activities ("Just because it's operating doesn't mean it's working.") focus on avoiding energy usage when pieces of equipment and processes are not in use or are not adding value by simply switching them off. This type of activity requires only basic knowledge of the process under study as it only checks for a mismatch in energy usage and product output or production schedule. It is considered as the first priority as it requires low (or no) investment, is easy to implement and generates immediate savings. If this step is overlooked, further changes could be suboptimal as the basic energy demand is not optimised. Therefore the *Stop* activities provide a basis for further improvements. When all *Stop* opportunities are exhausted, the next attitude in the hierarchy can be investigated.

The *Eliminate*/*Remove* activities ("Why is this equipment needed?") are less obvious and require a full/deeper understanding of the process, how it operates and whether it can be done differently. These activities focus on eliminating permanently superfluous processes and associated energy usage when a process can still be performed correctly without additional input. The example provided by Toyota for this attitude was the use of gravity and rollers instead of a conveyor and motor to transport parts from one place to another. The *Eliminate*/*Remove* opportunities, although relatively easy to implement, are not always easy to identify. Alternative approaches to perform a given function are not always obvious if they exist at all; and if they do, the difficulty remains in bringing it to the manufacturer's knowledge.

After these two first attitudes are covered, Toyota moves to the second stage with *Repair* and *Reduce* attitudes to reduce process energy base load (fixed energy consumption). The *Repair* activities ("Are we losing energy as a result of the breakdown?") also require knowledge about the functioning conditions of equipment and processes. They focus on matching the actual energy usage with the technical specifications of the equipment or process. These activities result in an improved output-to-input ratio by eliminating unnecessary waste (undesirable output) while maintaining product output (useful output). They are relatively low cost as they do not require the installation of additional equipment. However they are more costly than the *Stop* and *Eliminate*/*Remove* activities as they increase the maintenance cost on the short-term, although the savings generated through reduced energy usage and operational cost might fully compensate on the longer-term.

The *Reduce* activities ("Why do we need so much?") focus on reducing energy usage to meet the minimum requirements for a given process. This type of activity improves the ratio output-to-input as the *Repair* activities, but the focus here is on minimising the energy input rather than the waste output. This fourth step in the *6 attitudes methodology* is also crucial to avoid suboptimal improvement and is the last step to minimise basic energy demand before looking for reuse (*Pick-up*/*Trade*) and substitution (*Change*) opportunities.

When the two first stages are completed through the required amount of C-PDCA loops (Shewhart, 1939), Toyota moves to the third stage with *Pick-up* and *Change* attitudes which focus is on advanced efficient technology improvement and installation. The *Pick-up*/*Trade* activities ("Don't throw it away. Can't you use it somewhere?") look for reuse opportunities where the output of a process considered as a waste can be converted into an input for the same or another process. These activities attempt to create closed-loop or open-loop circulation of resources. They are very powerful improvements as they allow the energy usage of individual or groups of processes to be decoupled from the total energy consumption of the system: by reusing resources internally, the system reduces its dependence on external sources and thus improves its overall productivity. The main difficulty of this type of activities is to maintain the value of the resource flow when it becomes "waste" so that it can be reused with limited treatment. The more a resource flow loses value (thermodynamic or quality), the more difficult it is to reuse it.

Finally, the *Change* activities ("Is there any cheaper source of energy?") focus on technology substitution to replace inefficient, malfunctioning or obsolete equipment. These activities are typically the last resort as they are the most costly and require high investment in new equipment. However, *Change* attitude can also be the first step in the hierarchy. This would be the case for new process design or refurbishment of an old process: there is no current investment and thus the best environmental option can be considered, e.g. installation of high efficiency equipment corresponding to *Change* attitude, before going around the loop with *Stop*, *Eliminate*, etc. to improve this newly installed equipment or process.

6.4 Tactics Prioritisation with the Improvement Hierarchy

The improvement hierarchy combines the energy and waste hierarchy from the literature energy and waste hierarchies (Dovì et al., 2009; Sarkis and Rasheed, 1995; Lund, 2007; Blackstone, 2011) with Toyota's approach to energy reduction. Figure 6.1 illustrates all those hierarchies. The industrial approach to energy reduction discussed in the previous section helps to understand how manufacturers are undertaking improvement activities, i.e. at which level of the hierarchy they start given a particular context and how they progress through the levels of the hierarchy in an iterative way. This understanding is key for the development of the improvement hierarchy and to reorganise the tactics library: it provides an efficient sequence to identify more fundamental improvements with minimal invested effort first (e.g. stop and repair equipment), before moving on to increasingly complex and difficult improvements (e.g. optimise production schedule, optimise process set points and reuse waste).

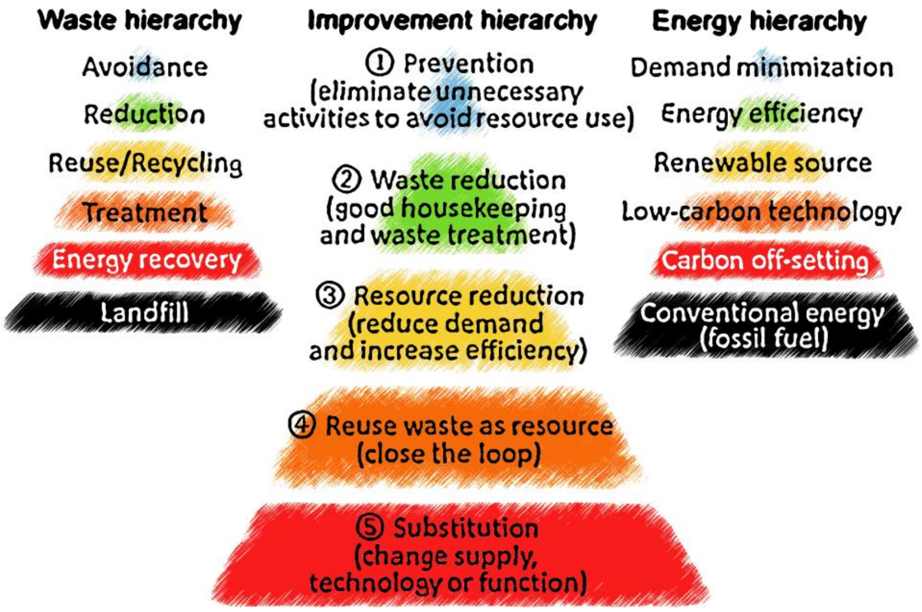


Figure 6.1. Improvement hierarchy

The prevention strategy focus on eliminating unnecessary processes or resource input. To access the **prevention** tactics, it is important to note that the two "remove" tactics (A21 and A41) can be difficult to identify as they require expert knowledge to recognise the unnecessary process which can be removed. The two following prevention tactics are comparing patterns between resource usage or process controls and production schedule (or product profile) to identify when equipment can be stopped or put in stand-by mode. The data collected in this instance comes from multiple sources requiring close collaboration of multiple functions. For example, the production schedule data will come from Planning or from Manufacturing Operations, whereas the resource consumption data may come from Facilities Management. Data may also be automatically connected (or there may arise a requirement to automatically collect data) which would involve IT functions.

Then other forms of prevention are the reduction strategies. The waste reduction strategy focuses on reducing or eliminating unnecessary waste or losses. The **waste reduction** tactics are good housekeeping activities focusing on waste outputs to reduce waste and losses or to maintain the value of the output through adequate treatment and management. These improvements are considered as relatively easy since they allow quick savings in resource and cost compared to the efforts invested. But manufacturers' knowledge about their waste is often limited and thorough data collection must be conducted to identify waste patterns. Such improvement would preferably target the largest or specific (e.g. based on toxicity, scarcity or cost) resource consumers and waste generators.

The input reduction strategy focuses on reducing demand, matching demand and supply, and on efficiency improvements which would reduce the resource consumption. The **resource use reduction** tactics focus on the inputs to increase the system's efficiency. Patterns in demand and supply profiles needs to be tested both in a static and dynamic way. The tests compare the magnitude of supply to the minimum requirements to better match the demand-side. Typical examples include compressed air pressure and cooling water temperature. Simulation is also used to optimise the timing of the resource flow which can result in overall efficiency improvements (avoid peak consumption or reach the optimum demand level to match equipment high efficiency point of use). The simulations require a large amount of data, thus those improvements can be identified only based on advanced analysis of the system. Additionally, the waste reduction is not necessarily proportional to the input reduction as with the previous strategy (waste reduction), e.g. fixed losses in distribution network for steam or compressed air. Finally, the most difficult reduction improvements are demand optimisation by challenging the set points or altering production schedules as these can only be done with deep knowledge of the processes and production system.

The reuse strategy focuses on reusing waste output as a resource input within the system. The **reuse** tactics focus primarily on the waste flows and look for opportunities to reuse waste output as a resource input. The use of a simulation tool is an important asset to allow systematic search for compatible waste and demand in the system taking into account the complexity of the system modelled, the timing of the flows and the spatial dimension. These improvements must be done after the prevention and reduction improvements are exhausted as wastes must be eliminated or minimised before looking for reuse opportunities. Reuse improvements are the hardest of all to implement; in industrial processes the sheer extent and grades of material, energy and water make this aspect a significant and iterative challenge.

The substitution strategy focuses on adding or replacing resource input and technology to improve the overall system's performance. The **substitution** tactics can be identified at early stage of the modelling by recognising inefficient components (based on equipment information such as capacity, efficiency and age) or black-listed resource inputs (e.g. toxic, non-renewable, non-reusable). This type of improvement is the most commonly found in industrial practice: replacing a piece of equipment or a process by a more efficient one or a less environmentally damaging one is a quick way to increase the sustainability performance but likely at high cost. It involves large scale changes by improving the source of supply and using high efficiency technology. Similarly to reuse tactics, the prioritisation of these substitution improvements must be done after other types of improvement are exhausted to avoid replacing a technology when a process can be stopped or to avoid oversizing equipment when the demand can be reduced.

Table 6.2 summarises the strategies of the improvement hierarchy. It is important to note that whether prevention or substitution is chosen first or not depends on the context of application as with the attitudes: for a new process or a refurbishment, the substitution strategy is first while improvement activities on an existing process will prioritise prevention.

Also, by conducting improvements at the top of the hierarchies (prevention), some of the improvements lower down cease to be necessary: if resource use of a particular process is fully prevented, then there is no need to reduce input or substitute the process. Therefore following the hierarchies to identify improvement is an iterative process: reuse strategy (e.g. waste-to-energy) and substitution strategy (e.g. renewable energy sources) join with prevention strategy (e.g. eliminate the significant item by deletion or substitution). The prioritisation of preferred options can be also based on practical considerations (i.e. the "easy" things first) or based on philosophical ideas (i.e. the "right" things first).

Table 6.2. Improvement hierarchy for resource efficiency (Despeisse et al., 2012a)

1	**Prevention by avoiding resource use:** eliminate unnecessary elements to avoid usage at the source, stop or stand-by equipment when not in use.
2	**Reduction of waste generation:** good housekeeping practice, repair and maintain equipment.
3	**Reduction of resource use by improving efficiency:** optimise production schedule and start-up procedures, match demand and supply level to reach best efficiency point of use of equipment or improve overall efficiency of the system.
4	**Reuse of waste as resource:** look for compatible waste output and demand, understand where and when waste are generated and whether it can be used as resource input elsewhere considering the complexity of the system.
5	**Substitution by changing supply or process:** renewable and non-toxic inputs, replace technology and resource for less polluting or more efficient ones, change the way the function is achieved to allow larger scale improvements.

Table 6.3 shows the library of tactics with the sequence in which improvements should be implemented – however it is not usually the sequence in which improvements are identified. Additionally, it is often more difficult to identify an improvement than it is to implement it. In some cases more data is required to identify "low-hanging fruits" (e.g. switch off and repair equipment) whereas replacing elements of the system at high cost can be identified quickly (e.g. replace fossil fuels by renewable energy sources or old inefficient equipment by best available technology). Keeping this challenge in mind, the library of tactics can be restructured following the prioritisation order of the improvement hierarchy rather than the first potential improvement identified. The tactics library designed in Chapter 5 was presented based on the type of system modification (A-labels, Table 5.3). The library of tactics as used in the improvement methodology presented in the next section is restructured according to the improvement hierarchy as shown in Table 6.3.

6.5 Chapter Summary

The tactics library introduced in the Chapter 5 was structured based on A-labels (type of modification) as this first categorisation helped to check the completeness of the library. In this chapter, sustainable manufacturing strategies and principles from the literature and an industrial approach to energy reduction were synthesised into an improvement hierarchy to guide the user in implementing tactics. The improvement hierarchy was developed using the manufacturing ecosystem model and sustainable manufacturing strategies to identify at which stage tactics should be implemented. The library was thus reorganised to prioritise tactics based on the improvement hierarchy.

Table 6.3. Tactics library structured according to the improvement hierarchy

1 Prevention
A11 Align resource input profile with production schedule
A21 Remove unnecessary resource usage
A33 Switch off/standby mode when not in use
A41 Remove unnecessary technology
2 Reduction (waste generation)
A15 Waste collection, sorting, recovery and treatment
A31 Repair and maintain
3 Reduction (resource use)
A12 Optimise production schedule to improve efficiency
A13 Optimise resource input profile to improve efficiency
A32 Change set points/running load, reduce demand
A34 Monitor performance
A35 Control performance
A25 Change resource flow layout
A45 Change technology layout
4 Reuse
A14 Synchronise waste generation and resource demand to allow reuse
A24 Reuse waste output as resource input
5 Substitution
A22 Replace resource input for better one
A23 Add high efficiency resource
A42 Replace technology for better one
A43 Add high efficiency technology
A44 Change the way the function is accomplished

The improvement hierarchy is used to restructure the tactics library and prioritise tactics to support systematic identification of improvement opportunities through cross-functional factory modelling (see the *improvement methodology* in next chapter). The modelling approach was developed in a previous study (Despeisse et al., 2012b) and integrates material, energy, water and waste (MEW) flows at factory level by combining buildings, facilities and manufacturing operations analysis.

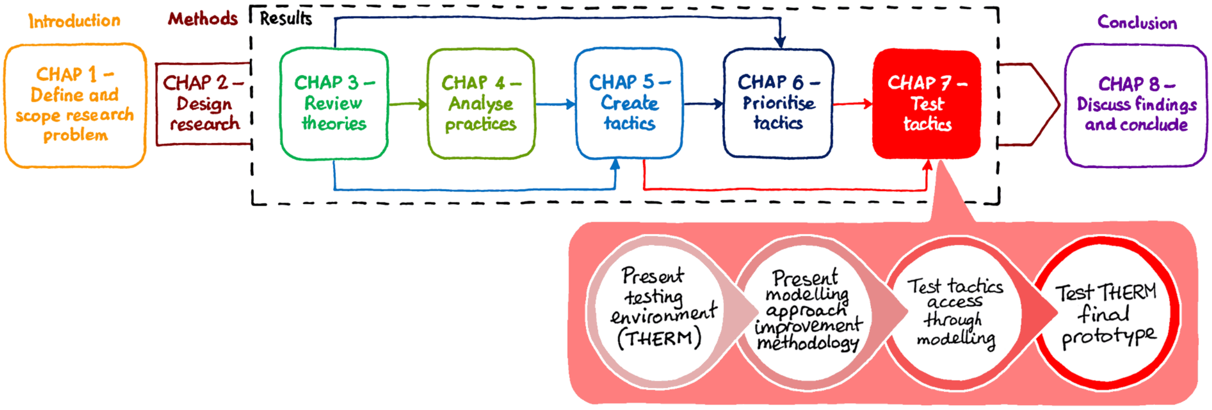
The improvement hierarchy addresses the second research question as it guides the improvement implementation process following a sequence that prioritises improvement options to enable a logical and methodological identification of opportunities:

- Resource input (prevention): eliminate unnecessary elements to avoid usage at the source, stop or stand-by process when not in use.
- Waste output (waste reduction): good housekeeping practice, repair and maintain equipment to reduce waste generation.
- Component ratio output/input (efficiency): optimise production schedule and start-up procedures, match demand and supply level to reach best efficiency point of use of equipment or improve overall efficiency of the system, replace technology and resource for less polluting or more efficient ones.
- Waste output conversion into resource input (synergy): look for compatible waste output and demand, understand where and when waste are generated and whether it can be reused as resource input elsewhere considering the complexity of the system such as using waste heat from one process as pre-heat for another process.
- Replace input or technology components (substitution): renewable and non-toxic inputs, change the way the function is achieved to allow larger scale improvements.

Chapter 7 IMPROVEMENT METHODOLOGY

Part of this chapter has been published in **Despeisse, M., Ball, P. D., Evans, S. and Levers, A. (2012), "Industrial ecology at factory level – a prototype methodology",** ***Proc. IMechE Part B: J. of Engineering Manufacture*** **226(10), pp. 1648-1664** *and has been submitted in* **Despeisse, M., Oates, M.R. & Ball, P.D., "Sustainable manufacturing tactics and cross-functional factory modelling",** ***J. of Cleaner Production*** **[In Press, Accepted Manuscript, Available online 15 November 2012]. DOI: 10.1016/j.jclepro.2012.11.008** of which the thesis author was the main contributor.

In this chapter, examples of application are used to check the applicability and validity of the tactics library. To so, the tactics are integrated into an improvement methodology for factory modelling and systematic identification of improvement opportunities. Prototype applications were used to test various aspects of the work: modelling approach and process data, access to and selection of appropriate tactics, and improvement methodology.



7.1 Introduction

7.1.1 Focus of this chapter

Until recently most improvements in manufacturing have focused on product flow, flow time, wasteful activities, and the capability and reliability of processes which are covered by lean manufacture principles (Womack and Jones, 1996; Bicheno, 2004). The review of industrial cases presented in Chapter 4 demonstrates that sustainable manufacturing practices (SMPs) can increase business performance and competitiveness. Whilst reported practices are good examples of what has been achieved, they are often company specific and difficult for others to reproduce since they provide few, if any, details on how improvements were achieved. Sustainable manufacturing strategies offer insight to the overall approach taken by companies but they can lack practical support for implementation.

Production systems cannot exist in isolation from the facilities that support them or the buildings that surround them as they too have significant impacts on sustainability, especially with regards to energy. Most approaches fail to consider material, energy, water and waste (MEW) flows throughout operations, facility and buildings systems. They also fail to recognise the value of wastes as they can be reused within the system rather than treated as losses to the system. The authors argue that to achieve sustainable manufacturing, waste must be interpreted in the widest form and includes water, heat and other energy forms. Production wastes have long been a concern for manufacturing improvement but the attention is now increasing on overall waste, energy efficiency, and occasionally energy waste.

This perspective on building services, manufacturing operations and facilities has been acknowledged by other authors (Ball et al., 2009; Herrmann and Thiede, 2009; Hesselbach et al., 2008). However, using tools such as modelling to support improvements across these areas is challenging as they are discipline specific. Additionally disciplines such as production engineering and facilities management operate in isolation and focus on local improvement rather than system level improvement. This is despite manufacturing operations using and discarding energy with the support of facilities. Therefore improvements in energy and other resource use to work towards sustainable manufacturing have been suboptimal.

By capturing systemically the MEW flows throughout the manufacturing system, potential interactions between processes, facilities and buildings can be identified to recover material and energy losses, "capture" them and use them elsewhere as resources. Using a systems view is a key element to move towards solutions which bring opportunities to improve the system as a whole and avoid local, suboptimal solutions. With knowledge of the potential flow interactions, design methodologies can be developed to enable more environmentally sustainable manufacturing system creation. Recently published papers have explored modelling tools as a support for sustainable manufacturing (Heilala et al., 2008; Herrmann and Thiede, 2009; Lee et al., 2012). The use of discrete event simulation, energy management system and manufacturing execution systems can help improving the interaction between production and building systems (Michaloski et al., 2011; Heilala et al., 2012). Such work has demonstrated the capability of modelling in principle but is as yet not supported by an overall integrating modelling concept.

7.1.2 Objectives and deliverables

This chapter reports three prototype applications to validate the tactics library and its associated improvement methodology for application through a factory modelling approach in which buildings, facilities and manufacturing operations are viewed as inter-related systems. The prototype applications demonstrate how improvement opportunities can be identified in a structured and systematic way via the use of tactics and manufacturing system modelling. This novel modelling approach integrates of MEW flows in a manufacturing unit and challenges current open-loop thinking by adopting of a manufacturing ecosystem view of a factory. The objectives of the project are to improve overall resource efficiency in manufacturing and to exploit opportunities to use energy and waste from one process as potential inputs to other processes. The novelty here is the combined simulation of production resource flows and building energy use and waste in order to reduce overall resource consumption.

7.2 Requirements for the Tool Development

Quantitative analysis is needed to assess the environmental impact of manufacturing activities as well as the benefits of potential improvements. The ever increasing number of principles and tools for sustainability in business shows a lack of integration between them (Baumann and Cowell, 1999) and in some cases can create confusion and lead to success being limited (Baas, 1998). This research intends to complement and consolidate other researchers' work in the field of sustainable manufacturing.

Existing modelling tools provide energy analysis in building modelling (Al-Homoud, 2001; Pérez-Lombard et al., 2009), product flows and timing of process flows in manufacturing (Pandya, 1995), but none covers all aspects to account for all resource flows, intermittency of processes and spatial dimensions. They also do not provide the means to find opportunities directly, many of which involve complex data manipulation and visualisation.

The inclusion of buildings and facilities in manufacturing process analysis has been considered by manufacturers such as Toyota (Hope, 2008). However, the analysis is largely manual and limited in complexity and completeness due to the lack of supporting tools. Therefore buildings and manufacturing facilities are still typically considered separately (Oates et al., 2011b).

As with lean/green approaches and manufacturing modelling tools, new methodologies and techniques require incremental development to be refined and to include all elements needed to support the design and analysis of sustainable manufacturing systems (Jahangirian et al., 2010). Tools supporting sustainable manufacturing must capture the interactions not only within the manufacturing system, but also with its physical environment, i.e. the manufacturing processes, their supporting facility, the surrounding buildings as well as some influential external factors (weather conditions and neighbouring industries and infrastructures). The analysis has to account for location and time in a manner that is not supported by either manufacturing process simulation tools or building energy tools. There are currently no tools commercially available for manufacturers to assess environmental performance, identify improvement areas and help suggesting specific actions across the breadth of the application area just described.

The next section presents the cross-functional factory modelling approach and the process data required to create a model of the manufacturing system being investigated. This model is then used to analyse the process data and access tactics to identify improvement opportunities. The prototypes show that the analysis can be applied at different resolution levels to derive opportunities incrementally as efforts in data collection and modelling are increased.

7.3 Cross-Functional Factory Modelling and Improvement Methodology

Prior to the collection of process data discussed in section 5.3.1, a factory model that brings together research disciplines is required. Modelling is used to guide the user through the steps of collecting data and understanding their manufacturing system before undertaking improvement activities. The manufacturing ecosystem model introduced earlier in Chapter 1 (Figure 1.3) captures the resource flows through the factory using the manufacturing ecosystem model developed by the researcher (Despeisse et al., 2012a).

7.3.1 Modelling approach

The manufacturing ecosystem model is based on the Industrial Ecology model type II (Graedel, 1994) which aims at increasing the system's overall efficiency rather than the efficiency of individual components of the system. By reducing the overall input associated with resource depletion and undesirable waste and pollutants outputs of the complete system, dependency on external resources and sinks is reduced. There is potential to extend beyond the factory gate to suppliers, neighbouring industries and other economic sectors. The inherent difficulty with factory modelling is the complex nature of MEW flows. These difficulties are exemplified when MEW flows cross functional boundaries. The systematic approach presented here aids in identifying functional boundaries and collection of data.

The analysis promotes factory-wide improvements (gate-to-gate perspective) to retain the value of resource and avoid environmental degradation. The authors recognise the need for a more holistic perspective on industrial systems and on society if sustainability is to be achieved. The boundaries have been set so that the manufacturer has full control on all elements in the studied system. The work excludes certain aspects of sustainability such as social and economic impact, since they are considered as positive side-effects of the work conducted rather than objectives. Also, the resources here are only energy, material, water, chemicals, waste, etc. (MEW flows) and not capital, employees, etc.

This manufacturing ecosystem model integrates the three main subsystems and process data described in Chapter 5 and combines modelling functionalities from both building and manufacturing disciplines:

- Manufacturing operations: manufacturing process systems (boundaries and connections), associated equipment (links to process systems), material flows (added value product, non-value added waste, and process system flow paths);
- Supporting facilities: facility equipment, inputs to manufacturing operations (e.g. compressed air, steam, cooling water), outputs (e.g. exhaust fumes, waste heat);
- Surrounding buildings: building geometry, construction data, weather data, HVAC systems and internal gains.

7.3.2 Improvement methodology

The improvement identification must follow a sequence that links the improvement hierarchy and tactics to the process data. The improvement methodology shown in Figure 7.1 has been developed to support a structured and systematic identification of sustainable manufacturing improvements using tactics. It combines the ecosystem view for factory modelling (Despeisse et al., 2012a) and the improvement hierarchy for prioritising strategies and tactics. It requires involvement of multiple actors to collect the data, and to validate and implement the output. Thus, although it is possible to perform the improvement methodology with a single user, the overall process is a highly collaborative one.

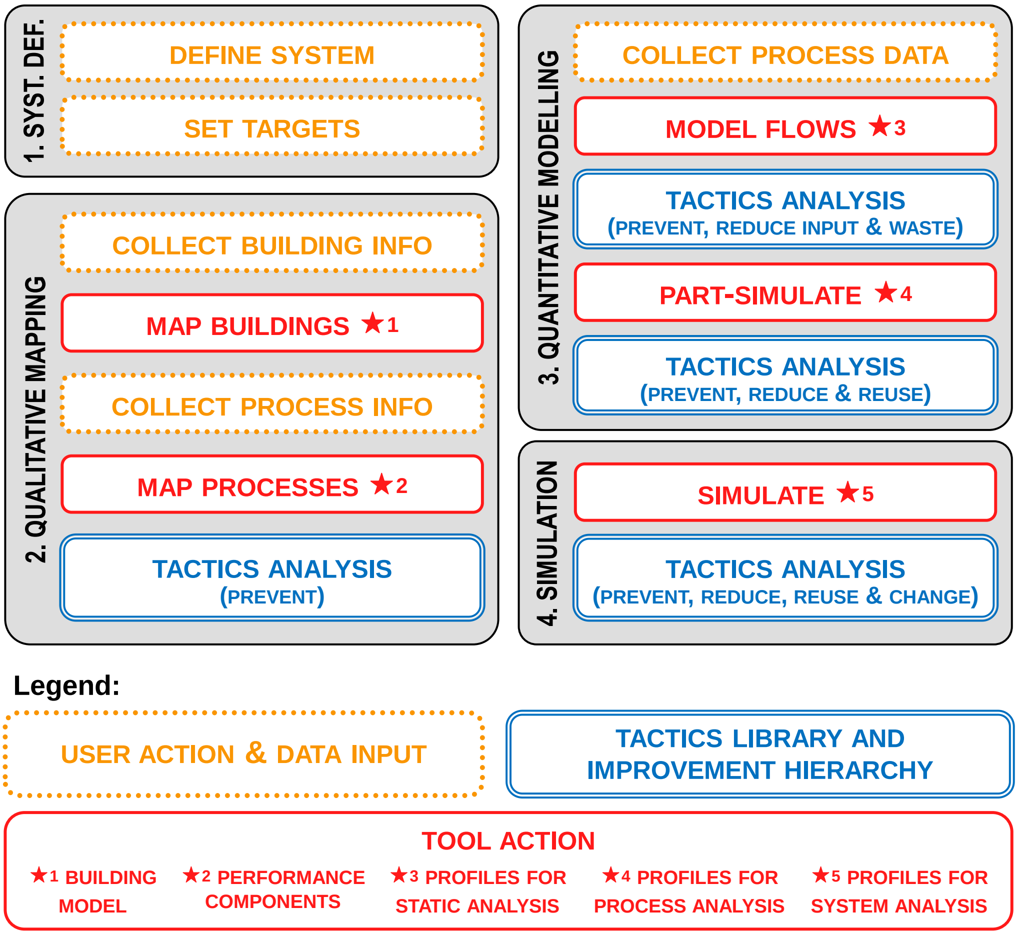


Figure 7.1. Improvement methodology for factory modelling and resource efficiency

Additionally the five tactic groups from Table 6.3 are all applied to some extent at all stages of the improvement methodology. Thus it is possible to find quantitative improvements as the data resolution builds up: at each stage the resolution is increased to find more opportunities. This is a key outcome because it shows a stepwise approach with increasing investment of effort; it also shows that some easy wins are possible with minimal invested effort.

The first step of the improvement methodology is to define the system boundaries and set the targets. Typical targets are CO_2 reduction, energy savings, water preservation and waste reduction. A factory "walkthrough" and detailed description of the processes by a specialist are conducted at this stage to gain deeper understanding of the processes selected for the analysis which is carried out in steps 2, 3 and 4. Typical system boundary definition is delimited by specific processes with multiple equipment or machines and physical areas of the factory such as buildings. Ideally the system would correspond to the complete factory and the flow map would stop at the factory gate. This is achieved through iteration where subsystems are put together until a complete model of the factory is obtained.

The second step is qualitative mapping. A first mapping is done to create the building model in which elements will be placed. The elements of the model are the buildings, the technology components placed in and near the buildings, and the resource flows linking all elements of the model (inputs: energy, material, water, chemical; outputs: product and wastes). The elements within the system boundaries previously defined are mapped against the factory layout to integrate spatial aspects into the model. The list of processes and equipment as well as their sequence for various flows are also defined: the most common way of defining the process sequence is to follow the product flow, but other sequences must be defined to follow the utility flows such as compressed air, steam and cooling water. Inputs and outputs are documented so that each flow clearly links to the processes it goes to or comes from. It is important to consider the resource flows not considered as technological components' inputs (with no origin) and outputs (with no destination), but as entities themselves. Doing so will bring into focus the links and interactions between processes across functional boundaries and enables the user to adopt an ecosystem view of the manufacturing system studied. A first coarse analysis is carried out at this stage to check for data errors and consistency, and for unnecessary elements. Tips (based on best practice and best available technology) are provided during the mapping when black-listed elements are identified.

In the third step, the quantitative model is created by adding process data and creating profiles, i.e. metered data and characteristics of resource flows and technological components. All elements of the system must be characterised by process data. The model process data and the corresponding sources are listed in Table 5.4 (Chapter 5). When parts of the model are complete, simulation can be used to analysis the process data locally. This stage of the analysis identifies local improvement opportunities to prevent and reduce the use of resources, increase efficiency, and to reduce and reuse waste.

In the fourth step, the process data are used to simulate the system's performance. This stage is a factory-wide analysis which allows the system's behaviour to be understood and analysed using a simulation of the model components' properties and process data. This stage identifies factory-wide improvement opportunities with reduction in resource use by following a chain of constraints from process to process or potential reuse of waste output from one process elsewhere in the system. The use of a simulation tool enables such complex factory-wide improvement identification in an otherwise more limited analysis which can be difficult to achieve manually.

7.4 Initial Prototypes: Tactics Access through Process Data

This section presents the prototype applications to test the research findings. The initial prototype applications consisted of manually testing the factory modelling approach and the process data required to accessing tactics. Data from Toyota Motor Manufacturing (UK) (TMUK) and Airbus Broughton were used to create models manufacturing processes and their factory environment.

7.4.1 Drying tank

To create the factory model and represent the three sub-systems and links introduced above, all elements of the system are represented graphically (Oates et al., 2011a) and characterised by process data a listed in Table 5.4 (Chapter 5). The thermal and electrical energy flows within a factory environment are coupled with traditional building energy flow paths. Waste energy created by processes, e.g. friction, impact and laser cutting, are represented as internal gains. Material flowing through a factory environment from process to process will also absorb or release thermal energy to its surrounding environment. For example, thermal energy will be transferred when a component leaves a furnace or a refrigerator within an enclosed manufacturing process system, factory or external environment. The amount of energy absorbed or released is dependent upon temperature, geometry and material properties.

In the first prototype application, a model of manufacturing operations and facilities was created based on Airbus drying tank (Figure 7.2). It consists of material and energy flows, a drying tank and supplementary equipment such as fan, heat exchanger (HX) and air re-circulation ductwork. Air is drawn into a 18.5 kW fan from the factory environment. The air temperature increases to 40°C due to the transfer of thermal energy from a 200 kW HX and the input of work from the fan prior to entering the 90m^3 drying tank. A proportion of the air is re-circulated, and mixed with air drawn from the factory environment. The HX is a closed-loop water circuit connected to a combined heat and power (CHP) source. The HX water input is at 90°C and water output is at 80°C. Material in a wet state enters the process, is dried and moved back into the factory environment. The process is repeated for each batch that passes through the drying tank. The connections and links between the technology components and the resource flows are illustrated in Figure 7.2.

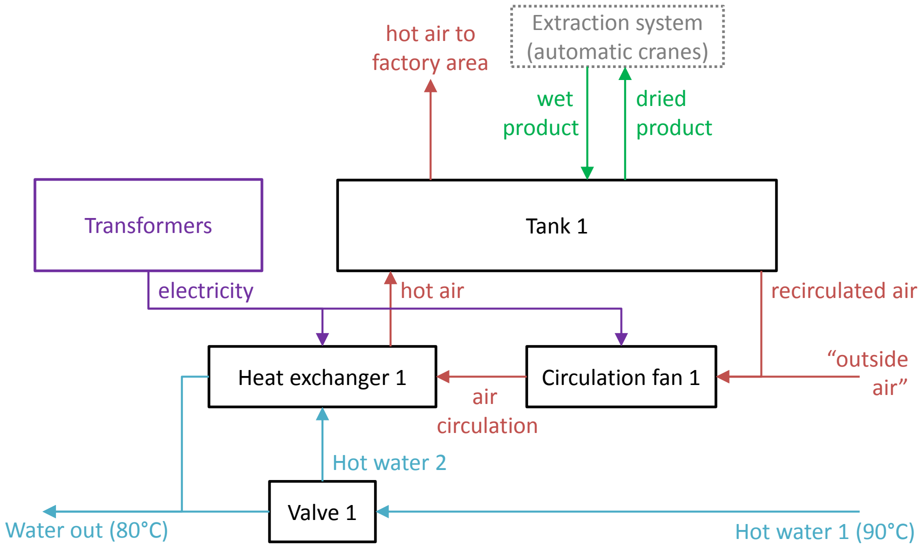


Figure 7.2. Simplified representation of the drying tank
Input of hot water to generate hot air to dry the product

Before the tactics analysis, the fan and HX were operating constantly although the drying process is intermittent. Using the tactics for *prevention* and *reduction* and the associated logic test on the process data available, the following improvement opportunities were identified:

1. Prevention

- *A11 Align operating time with production schedule*: identify mismatch between product profile and input profiles over time
    - Improvement 1 – Circulation fan electricity usage: no fan electricity usage when no material is in the tank
    - Improvement 2 – Heat exchanger electricity usage: no HX electricity usage when no material is in the tank
    - Improvement 3 – Heat exchanger water usage: no HX water usage when no material is in the tank
- *A33 Switch off/standby mode when not in use*: identifies mismatch between production profile and equipment/process operating time (technology component attributes of characteristics).
    - Improvement 4 – Fan and heat exchanger operating time: HX and fan are off when no material is in the tank

2. Reduction

- *A35 Control performance*: identifies mismatch between production profile and equipment/process performance level and suggest to add controls to adjust the performance to the minimum requirements (This is different from tactic A33 in that it also compares the magnitude of profiles, not only the timing)
    - Improvement 5 – Tank (or drying process) performance: process set points corresponds to the minimum requirements for product dryness
    - Improvement 6 – Fan and heat exchanger performance (or supply level): HX and fan supplying only the minimum required to Tank 1
- *A32 Change set points/running load, reduce demand*: identifies mismatch between minimum requirements and process set points (profile magnitude).
    - Improvement 7 – Reduce temperature set point: temperature set points to meet the minimum requirements for product quality (dryness)
- *A12 Optimise production schedule to improve efficiency*: identifies mismatch between minimum requirements and product profile (timing).
    - Improvement 8 – Reduce processing time: shorten process cycle time to meet the minimum requirements for product quality (dryness)

This first prototype validated the use of modelling to access tactics and showed that tactics can help identify improvement opportunities. This example will be used in section 7.5 for the final prototype.

7.4.2 Paint shop

Figure 7.3 shows a graphical example of an air supply house (ASH) for TMUK paint process in a primer booth. The function of the ASH is to condition air to meet the operational requirements of the paint booth (process set points: air temperature and humidity). The diagram represents the MEW flows across the system as resources are being consumed to draw air through the air conditioning processes by fans. The MEW flows are modelled from supply source to treatment (shaded boxes), to the equipment and process being investigated (clear boxes). The process sequence is as follow: (1) pre-heat section: gas burner, (2) humidification section: "Munster Biscuit" type humidifiers, (3) cooling section: cooling coil, (4) re-humidification section: steam injection, (5) re-heat section: steam heating coil, (6) final section: supply fans to draw air into the paint booth.

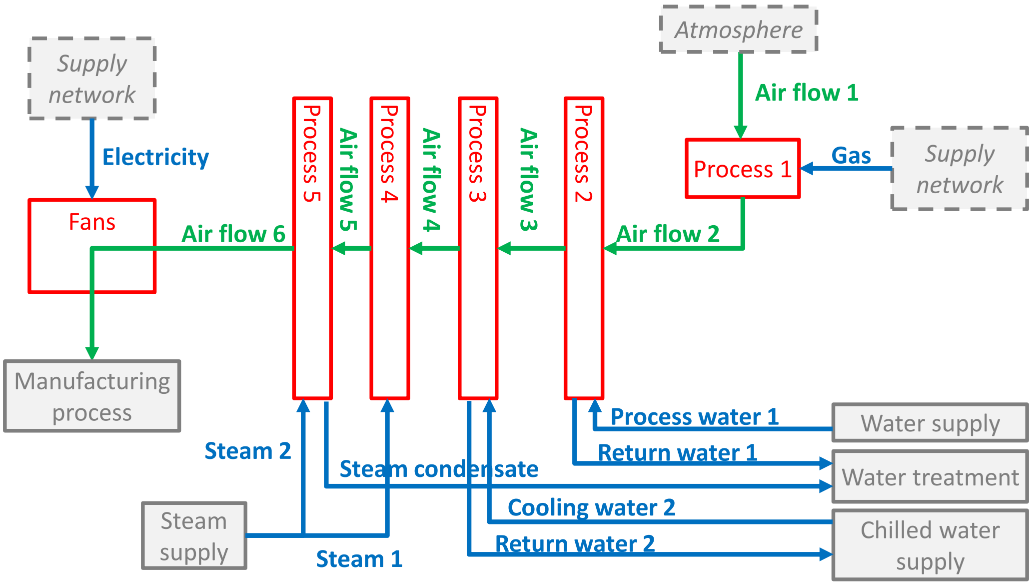


Figure 7.3. Simplified representation of an air supply system

The process data collected were used to characterise each element of the system: input and output profiles, air and water properties before and after each process, equipment capacity and actual running loads, process demand profiles and set points. Each process can be further detailed by breaking down a box of the diagram into a new diagram to show more details. For instance, Figure 7.4a shows a more detailed view of the chilled water supply. Depending on the data available—and therefore the process data used to characterise the system's components—different tactics are used to compare profiles, identify mismatch and inefficiencies, and suggest improvement options.

Following the sequence for improvement strategies and tactics as listed in Table 6.3, the prevention tactics were used to compare resource usage profile and production schedule, i.e. check whether resources were consumed during non-production hours. Then a comparison of total supply and sum of all usage allowed a check on completeness of the model and identify excessive losses occurring between supply and usage. In this particular example, the prevention and waste reduction activities were already applied.

The next group of tactics in the sequence is the resource use reduction. Tactics 3b and 3e identified an improvement opportunity by comparing the cooling water pump performance (running load, and therefore cooling water supply) to the cooling demand profile of process 3. As illustrated in Figure 2a, the pump was running full load all the time when the demand was significantly varying. An energy and water reduction opportunity was suggested as illustrated in Figure 7.4b: improve the equipment control to better match the supply to the demand. In this particular case, using an inverter with the pump allowed the water input to match the demand for cooling water.

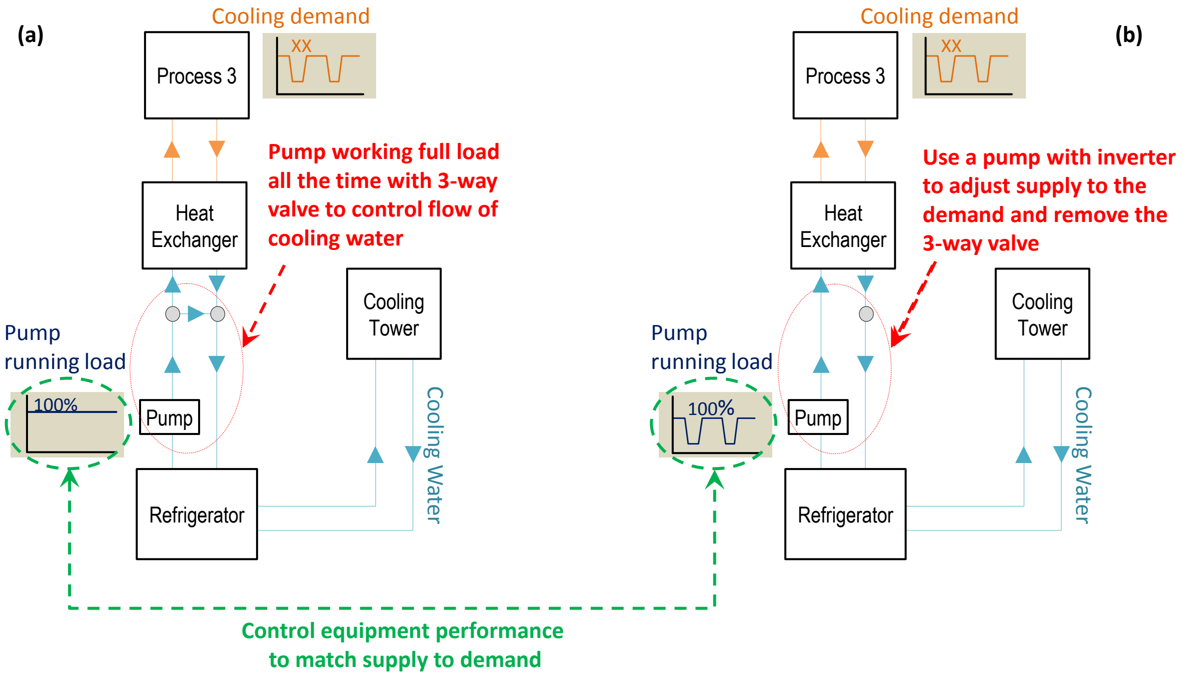


Figure 7.4. Chilled water system
(a) before improvement, (b) after improvement

This application example demonstrates that it is possible to identify improvements using modelling of MEW flows to connect the manufacturing facilities and operations and gain a better understanding of the interactions between them. The modelling tool developed can assist manufacturers in assessing the resource productivity with a systems perspective and help to manage resource flows more sustainably.

7.4.3 Kaizen examples

In the previous example, the system could be modelled in two different ways: instead of modelling the pump running load, one can modelled the cooling water flow or the pump performance curve to identify a mismatch between the pump operations and the process demand for cooling. This would result is the use of a tactic to identify improvements. In this section, examples of *Kaizen*[4] activities at Toyota were used to show how an improvement can be identified using different process data and consequently, different tactics.

In the Kaizen example below, the process is modelled using an energy profile and product profile (Figure 7.5a), and in a second model using a control profile and a product profile (Figure 7.5b). Based on the process data available to perform the pattern analysis, tactic A11 or A35 are being used to identify the improvement opportunity. Both models highlight a mismatch between the product profile and the process operating profile which is represented by energy usage in model (a) and by the equipment controls in model (b).

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[4] Japanese word for *improvement*.

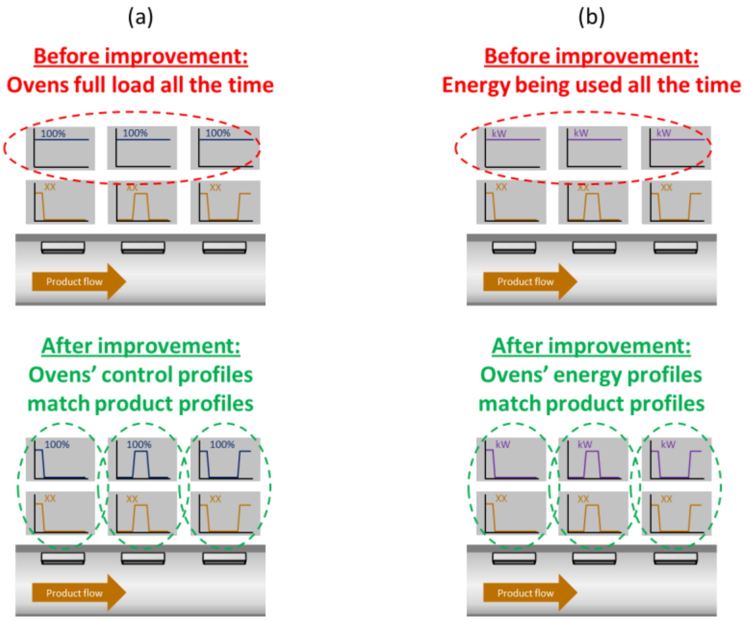


Figure 7.5. Multiple paths with different tactics to access a single improvement
(a) Tactic A11 – usage profile vs. product profile
(b) Tactic A35 – control profile vs. product profile

7.5 Final Prototype: THERM Software and Tactics Logic Tests

This part of the work was conducted collaboratively with the THERM partners: two universities (Cranfield University and De Montfort University), two manufacturing companies (Airbus UK and Toyota Motor Manufacturing UK) and a software developer (IES Ltd). The aim was to develop a modelling and simulation tool—the THERM software—which integrates sustainable building design and manufacturing process MEW flow analysis to supports sustainable manufacturing plant design and improvement (THERM Project, 2011; Ball et al., 2011).

The THERM project has developed the prototype IES Ltd <VE> THERM software which has been applied to industrial case studies to demonstrate the ability of the prototype to support activities towards sustainable manufacturing. The prototype applications presented in this section show how the research findings were integrated into the new IES software functionalities developed during the THERM project (Despeisse et al., 2013).

The following sub-sections describe the application of the improvement methodology based on process data provided by the industrial partners of the THERM project. The Airbus drying tank example was used for the development of this final prototype (the same process used in the initial prototype presented in section 7.4.1). This prototype application also highlights the collaborative nature of the work as it brings together manufacturing and facility engineers, shop-floor technicians, and energy managers:

System definition

The first step of the improvement methodology is *System definition* to define the scope of the analysis by setting system boundaries and targets. A factory "walkthrough" and detailed description of the processes by a specialist are conducted at this stage to gain deeper understanding of the processes selected for the analysis. Typical system boundary definition is delimited by specific processes with multiple equipment or machines and physical areas of the factory such as buildings.

A formulated team of industrial operations and facility engineers working in collaboration with the industrial, academic and software developer defined the focus of the study. Table 7.1 summarises the possible options for the analysis in the THERM software. Although the analysis can support the design of new factories, the case application focused on the analysis of an existing one. The assessment was carried out at the factory gate level first and then progressed into static process analysis noting that subsequent dynamic simulation capability was not used. The focus and measurement was energy reduction as water, materials, carbon and cost were considered to be the consequences of improvements in this particular case.

Information in the form of *tips* are available at each phase of the improvement methodology to provide generic advice based on the sustainability principles, a glossary to overcome the integration of two disciplines, and the collection of information and data, i.e. building and process data.

Table 7.1. Options for analysis settings

Assessment type	**Extent of assessment**	**Focus of assessment**	**Targets**
New	Factory gate	Energy	Energy
Existing	Design, map and measure	Carbon	Carbon
	Building and process simulation	Material and water	Material and water
		Cost	Cost
			Functional unit

Qualitative mapping

The second step of the improvement methodology is *qualitative mapping*. An early stage analysis focuses on the collection and examination of utility metered data to focus the analysis on specific resource flows or specific processes such as large energy consumers (Figure 7.6). This data usually consist of half hourly and hourly meter readings, logged by utility suppliers for billing purposes, e.g. electricity and gas. During early stage analysis there is no need for building geometry, process mapping or high resolution data. Sustainable manufacturing tactics (*A34 Monitor performance* and *A35 Control performance*) and *tips* help to identify the drying tank as a large energy consumer in the focal area.

Then the building and processes are modelled by creating *building geometry*, assigning construction data and placing technology components (processes) within the building. Ideally the system would correspond to the complete factory and the flow map would stop at the factory gate. This is achieved by taking a top-down approach with details being added by "zooming" on the processes of interest (in this case, the drying tank). This stage can be repeated to create subsystems which can be put together until a complete model of the factory is obtained.

The qualitative process model is created by *mapping processes*, i.e. placing technology components in the building model as illustrated with the yellow components in Figure 7.7. The building is a representative boundary surrounding the drying tank and supplementary equipment represented by the wire frame components in Figure 7.7. The elements within the system boundaries previously defined are mapped against the factory layout to integrate spatial aspects into the model. The list of processes and equipment as well as their sequence for various flows are also defined: the most common way of defining the process sequence is to follow the product flow, but other sequences must be defined to follow the utility flows such as compressed air, steam and cooling water. Inputs and outputs are documented so that each flow clearly links to the processes it goes to or comes from. It is important to consider the resource flows as individual entities in themselves, not simply as being assigned to equipment and processes as an input value with no origin and an output value with no destination. Doing so will bring into focus the links and interactions between processes across functional boundaries and enable the user to adopt an ecosystem view of the manufacturing system studied.

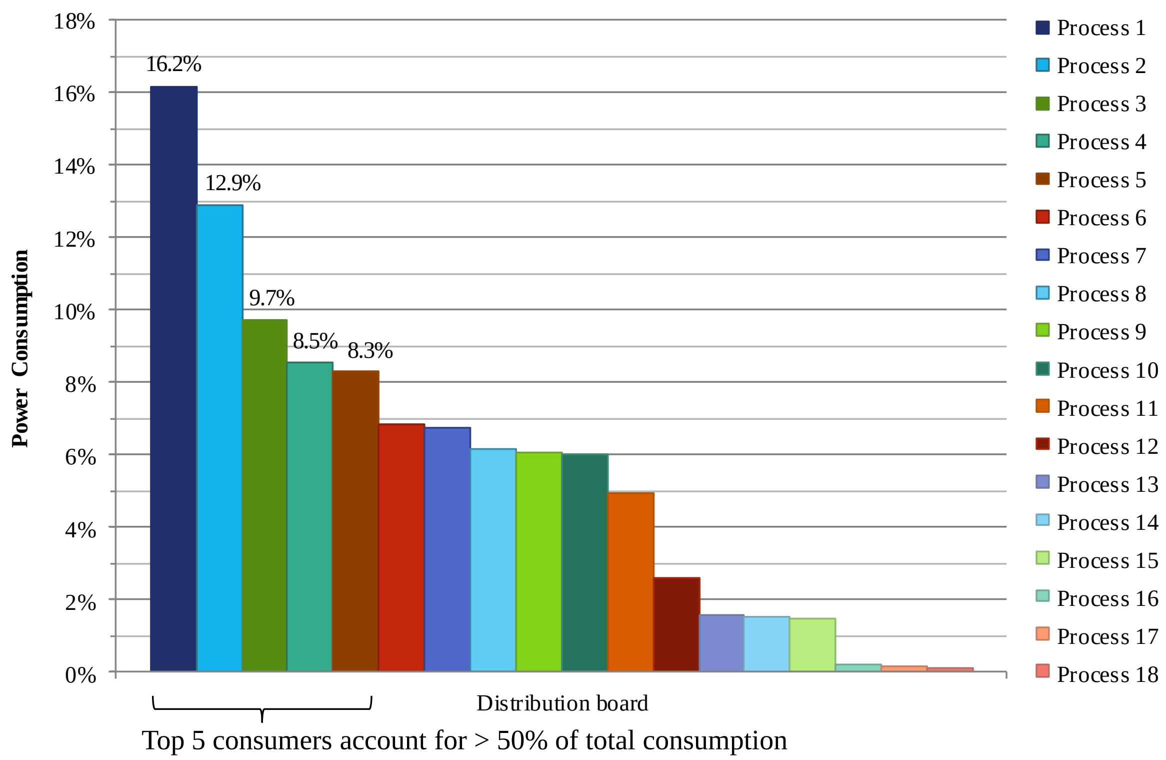


Figure 7.6. Processes ranked by annual power consumption

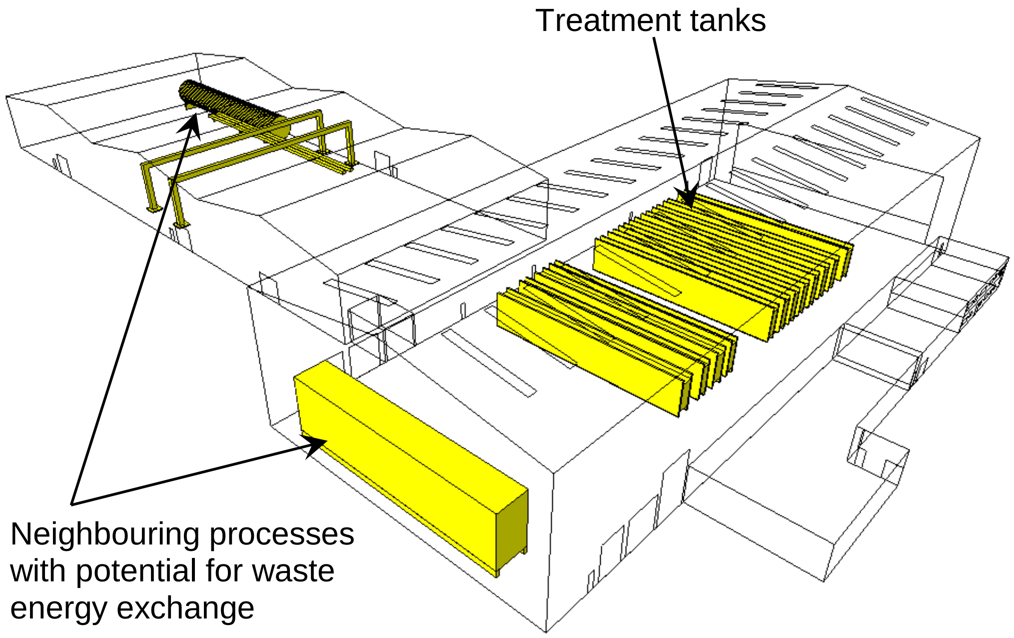


Figure 7.7. Building geometry (wire frame) and manufacturing processes (yellow elements)
The manufacturing processes are mapped against the factory layout to integrate spatial aspects into the model.

Quantitative modelling

The *quantitative modelling* phase is an iterative, non-simulation phase of the improvement methodology. The quantitative model is created by adding process data and creating profiles, i.e. metered data and characteristics of resource flows and technology components. All elements of the system must be characterised by process data. This stage can be repeated to add more data as they become available and increase the level of detail of the model. The list of model process data was introduced in subsection 5.3.1 (Table 5.4). To enable the quantitative analysis and identification of improvement opportunities, some process data are defined as constraints, mainly production schedule and set points. These constraints determine the minimum input requirements for the manufacturing processes to achieve the correct product quantity and quality. Additional variables characterise the technology components: capacity or equipment rating, running load (including the minimum and maximum demand, i.e. base- and peak-load), the performance or efficiency curve which define the ratio output/input as function of running load. Optional information can be added to increase the quality of the analysis, such as equipment depreciation and operating cost.

At this stage operational profiles are derived from sub-metered data and assigned to the fan, HX and drying tank process components discussed in step 4. Material flow profiles are derived from production schedules and assigned to the material component. The assignment of quantitative process data enables the improvement methodology to iterate through the manufacturing sustainable tactics. At this non-simulated stage of the improvement methodology, all of the tactics are activated with exception to reuse. A first pass of the tactics identified potential improvements. The prevention tactic was flagged due to a mismatch between the operational and production profiles (*A11 Align resource input profile with production schedule*). For example, the energy consumption profile of the equipment can be compared to the material flow through the process as highlighted in Figure 7.8 (values on the Y-axis are company sensitive data). The prevention tactic advises switching off the fan when there is no product being processed. Reduction tactics were also identified based on material drying times, tank temperature set points, equipment flow rates and ratings (*A32 Change set points/running load, reduce demand*). The alteration of equipment set points and reduction in material drying times to conform to minimal design condition need to be investigated in the future.

Simulation

In the seventh step, the process data is used to simulate the system's performance. When parts of the model are complete, simulation can be used to analyse a selection of process data locally. This stage of the analysis identifies local improvement opportunities to prevent and reduce the use of resources, increase efficiency and reduce waste. With the example given in Figure 7.8, the operational profiles of the fan and HX were modified in conjunction with the prevention tactic. There are potential energy savings when there is no product being dried within the process, illustrated in the figure by the filled areas: fan (green) and HX (blue). Simulated results predict a 74% energy savings from one week of data. Further potential savings could be achieved by restricting the drying time of the material to the minimal design condition and reducing set points. Due to the varied production flow of material that occurs on-site as a consequence of a batch process, the industrial partner has reduced the operation usage of the drying tank in line with shift hours and turned the process off outside these hours (e.g. weekends). Future work is to be carried out in line with the reduction recommendations, following consultations with operations and facility engineers. Outcomes from this prototype are also to be cascaded across other similar processes, resulting in further energy saving opportunities.

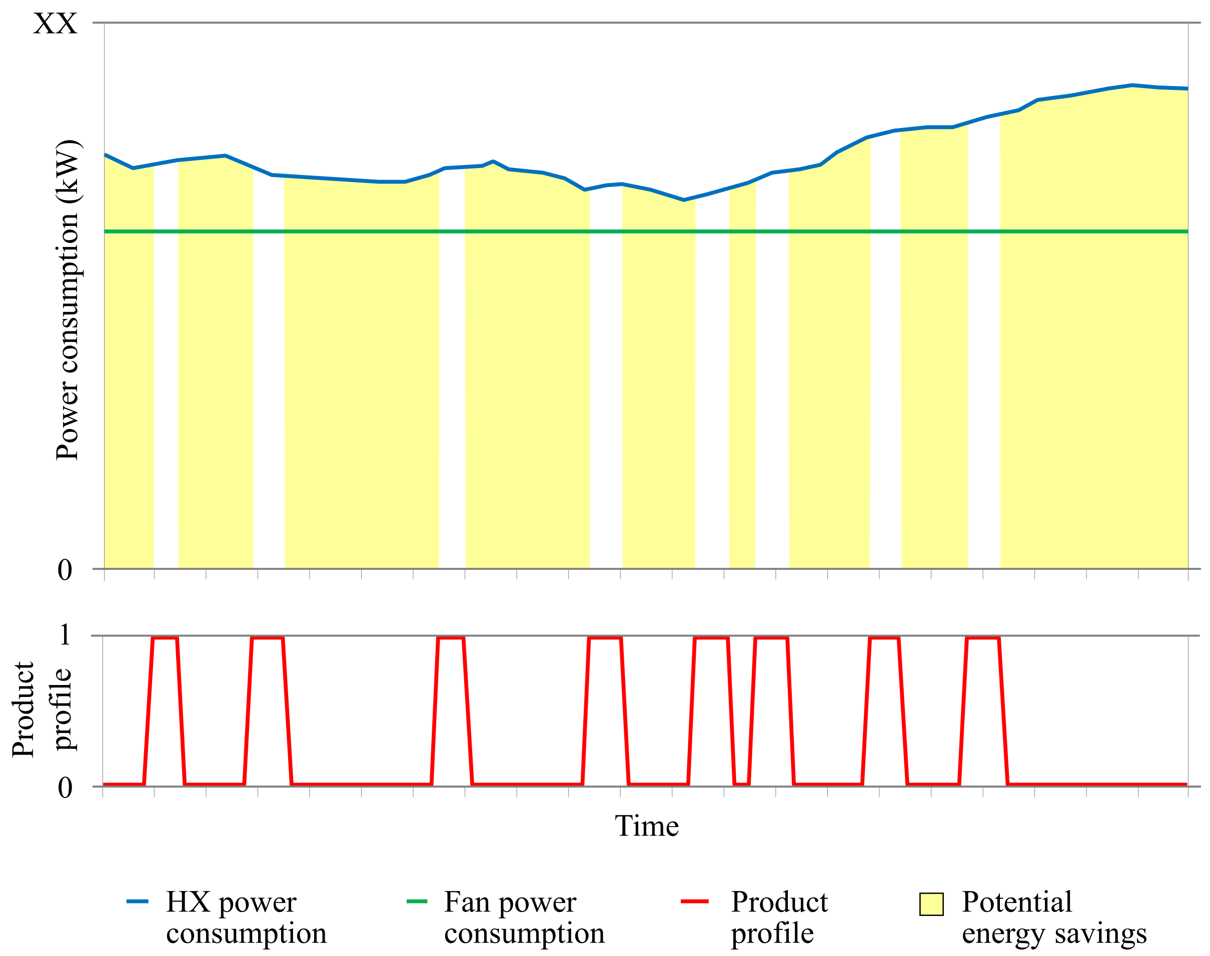


Figure 7.8. Process energy and potential savings using prevention tactic A11
The energy consumption profiles can be compared to the material/product flow to highlight potential energy savings (i.e. when equipment can be switched off)

When the system model is completed, the analysis identifies system-wide improvement opportunities with reduction in resource use by following a chain of constraints from process to process or potential reuse of waste output from one process elsewhere in the system. This phase of the work requires a fully functional simulation model, being developed as part of the THERM project. The building mapping requires that the user assigns HVAC data to factory thermal zones, and construction properties, weather data, room temperature set points, internal gains from lighting and room occupancy to the building. The simulated aspect of the works activates all of the sustainable manufacturing tactics. Following the same principle outlined in the non-simulation approach, the methodology cycles through the tactics identifying potential improvements. Further work will include enhanced functionalities to identify reuse opportunities (*A14 Synchronise waste generation and resource demand to allow reuse* and *A24 Reuse waste output as resource input*) such as highlighting processes in operation (in red in Figure 7.9) and highlighting based on thermal gradient, energy type, etc.

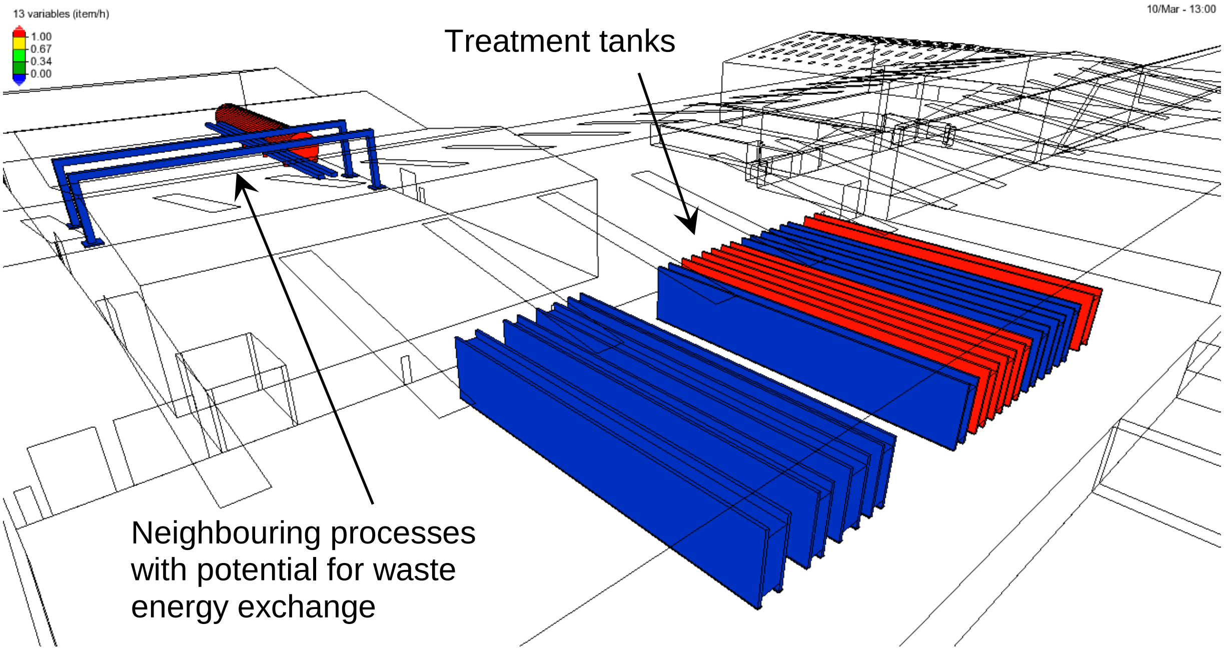


Figure 7.9. Simulated analysis highlighting opportunities for reuse
Colour coding: red: WIP – work in progress; blue: no WIP

7.6 Chapter Summary

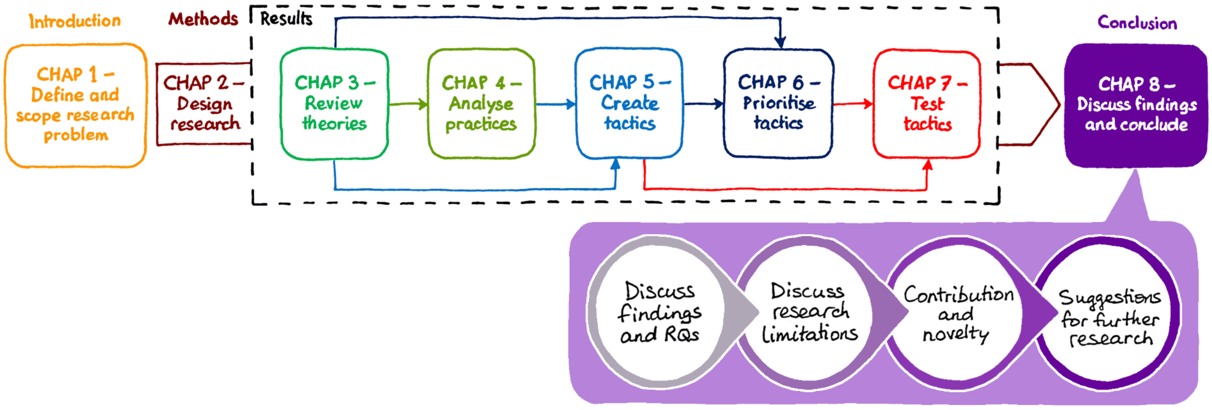
The modelling approach used for the THERM tool demonstrates the possibility to adopt an integrated systems view of a manufacturing system (or, in this case, a part of it) using the MEW flows through the operations, facilities and buildings. Typically, modelling and simulation techniques overlook wastes as they usually focus on process planning and product flow. At first, the use a top-down approach is recommended to identify the key consumers and focus the analysis on resource intensive processes. Then a lateral approach can be adopted to follow the MEW flow in further detail. This would help to steer the focus of the study towards interesting areas where potential improvement can be made, rather than spending a lot of effort to include areas which are not bringing much benefit to the study. If information is lacking, an approximate (but complete) model based on measured data is preferred to a more detailed one based on assumptions. When going into further details, if data are missing between two points with known values, it is possible to calculate the value of the flow to complete the model. Otherwise, the flow is considered as a loss to the system (such as heat that "evaporates" in atmosphere through the chillers or exhaust pipes/chimneys). After an understanding of the system is gained, further information can be obtained incrementally by working with the elements of the model that stand out as potential improvement areas. Details can be added by "breaking down" elements of the model to a lower level of abstraction.

It is also very important to clearly define what the boundaries of the system studies are. For instance, where do the material and energy flows begin? What are the activities included and excluded when it comes to "borderline" activities? A clear definition of boundaries is required to evaluate the performance of the system.

This chapter has shown testing of the tactics and improvement methodology with multiple prototype applications. They have shown that the use of tactics through factory modelling can support improvement identification. The final prototype tool also demonstrates the ability to represent the metrics necessary for evaluating options for more sustainable manufacturing system.

Chapter 8 DISCUSSIONS AND CONCLUSION

This chapter discusses the research problem after taking the results into consideration and demonstrates that the research questions have been addressed. The limitations of the research findings are also highlighted to open a discussion on possible alternatives and improvements. Then the contribution to knowledge and practice is discussed. Finally it presents potential future research in the area of sustainable manufacturing.



8.1 Research Findings Summary

Existing concepts and models for sustainable manufacturing cover a wide variety of topics and approaches: the need for resource efficiency in manufacturing is driven by cost, regulations, stakeholders' pressures, corporate reputation and awareness of the urgency of the situation. The move towards sustainability can only take place through extensive changes spanning from behavioural to technological changes, and through holistic perspective as well as local solutions. Therefore, the knowledge on the topic is highly multidisciplinary. Collaborations between disciplines and with industrial and governmental institutions are increasingly common in academic research as new challenges involve rapid technological change, interconnected and complex problems.

This research addresses the challenge of bringing industrial sustainability principles into manufacturing practice through a collaborative project involving two academic partners, two manufacturers and a software developer. This collaboration provided a multidisciplinary context for the research and also guided the work to deliver tangible results in the form of a modelling tool (software) which can be used directly by manufacturers to have a real impact on the companies' environmental sustainability performance.

By conducting a literature review and a case collection during the exploration phase of the research, the initial objectives and the first research question were addressed: understand what operational improvements are needed to approach sustainability, what improvements are currently achievable based on theory and industrial practice, and how these improvements can be codified to support their generalisation across industry. On the one hand, the exploration of sustainable manufacturing as a concept provided a better understanding of the global issues targeted and the proposed theoretical solutions (Chapter 3). On the other hand, the exploration of sustainable manufacturing practices (SMPs) provided an overview of existing operational solutions in the manufacturing industry (Chapter 4). The SMP analysis uncovered the main mechanisms of change which were used to codify the improvements and allow tactics to be formulated.

During the explanatory and testing phases, the tactics library and the improvement methodology were developed and refined to address the second research question: they provided a practical approach to identify improvement opportunities in a structured and systematic way. The tactics translate improvement mechanisms into simple, generic and clear rules which in turn help generalising SMPs (Chapter 5). The library of tactics was then organised according to an improvement hierarchy to prioritise tactics and provide a structured approach to operational improvements (Chapter 6). Finally, the tactics and improvement methodology were tested using prototype applications to demonstrate the ability of the research findings to support manufacturers in their journey towards sustainability (Chapter 7).

8.2 Discussions

8.2.1 Concept definition and system boundaries

While concepts of sustainability and sustainable development have become increasingly known in academia and industry, there are still different interpretations of what a sustainable level of performance is. In a similar way, concepts of pollution prevention, cleaner production and industrial ecology have gained importance over the last decade and have been used by many companies; but they still need to be strengthened to ensure wider success with more systematic application in industry. Looking back at the historic evolution of these concepts, clear and strong definitions are a key factor in the diffusion among practitioners of these concepts whether the superiority of their benefits are proven or not. For instance, although pollution prevention has been recognised as a better approach than pollution control and other end-of-pipe solutions for long-term results to reduce environmental impact of industrial activities, it has been less successful than pollution control approaches as they offer concepts with strong command-and-control policies and are consequently easier to implement.

Cases from books, conferences and academia mostly refer to sustainable manufacturing theoretical concepts as presented before in the literature of the field. Cases presented by the business community itself describe practices only in a technical and financial point of view; they infrequently adopt the existing terminology of sustainable manufacture used by academics. Thus a major difficulty in the dissemination of sustainable manufacturing practices in industry is the duplication of concepts and efforts, as well as the lack of understanding on what is the global impact of local improvements, e.g. the rebound effect. Activities in the newly developed field of sustainable manufacturing can be found under the different names: “sustainable production”, “green manufacturing”, “competitive sustainable manufacturing”, “environment conscious manufacturing”, “environmental benign manufacturing”, “environmentally responsible manufacturing”, etc. Multiple labels for similar approaches and vagueness in the definitions have led to a semantic confusion. This can be explained by the fact that sustainable manufacturing is a new field spreading in academia and the practitioner community but not yet adopted as a framework. This lack of unified framework is one of the main barriers to achieve successful application of sustainability principles in industrial systems.

Another debated area is the boundary definition of the system studied and improved as it has implications regarding the accounting method. For instance, carbon-neutral energy system usually means that there is no direct emission during the use phase of the energy system such as fuel cells or nuclear power plants. Renewable energy sources such as solar, wind and hydropower are other examples of carbon-neutral energy systems. Biomass also is considered to be carbon-neutral through the fact that growing the fuel captures as much CO_2 as it releases during its combustion. But taking a life cycle perspective, CO_2 emissions occur during manufacturing, commissioning, maintenance, in some cases harvesting of the fuel itself, and decommissioning; these are often ignored when comparing various energy systems. All impacts must be taken into account to ensure full understanding of the different technologies' long-term contribution for a more sustainable society.

Therefore, when quantitatively assessing manufacturing systems' performance, one must account not only for direct and local environmental impact, but for indirect and more global impact resulting from resource life cycle as well (i.e. from virgin material to products to reuse, remanufacture and recycle paths). By adopting different viewpoints, benefits and impacts can shift outside the system boundaries and become an externality, or conversely be internalised become part of the desired outcome. Typical examples are the different paths for closing the material flow: when considering only the factory, waste flows leaving the factory gate are completely lost for the system, but if these waste flows are resources for another industry, then a wider perspective can capture wider benefits for the industrial system. Another example is the product life cycle perspective: if product is being downcycled, from this product's life cycle perspective, no material is lost; but considering the material itself (resource flow and stock), virgin material will still be needed to produce this product while the material from the used products is degraded when downcycled, therefore the material loses its value.

In this research, however, the scope of the analysis was narrowed down to focus on the manufacturing system. By using the manufacturing ecosystem model, resource flows could be integrated across the manufacturing operations, the supporting facilities and buildings. Thus the factory analysis set its boundaries around the factory gates. The research recognises the importance of the bigger picture to optimise resource use and the need for a life cycle view on manufacturing activities to achieve environmental sustainability. Thus, when evaluating various improvement options, the researcher encourages adopting a wider perspective on society and Earth's systems to better account for the impact of change on elements outside the factory gates as illustrated by Figure 1.1 in Chapter 1.

8.2.2 Ecosystem model and prototype tool

The literature review revealed that there are no tools or techniques that effectively combine space, product flow, energy flow and time to enable complete modelling and analysis of resource flows in a factory. This work feeds into the specification for such a tool. The main objective of the modelling tool developed in this research is to improve the environmental performance of manufacturing systems. This can be achieved through overall resource efficiency (as opposed to individual process efficiency) and through closed-loop resource flow, thereby reducing the net resource inputs and waste outputs of the system.

Industrial ecology concepts, such as systems view, food webs and industrial ecosystems, are usually applied at macro-level involving various industries and local communities. In this research, they are applied at factory level in order to remedy the lack of integration in the design of manufacturing systems. Current approaches to factory analysis are overlooking potential interactions within the system: manufacturing processes are designed to have their own inputs and outputs, regardless of the possibility of reusing other processes' wastes as resources. Therefore a manufacturing ecosystem model was used in this research to adopt such perspective of the factory. Keeping in mind that all elements of an ecosystem are put together in order to constitute a synergetic system, the emphasis is on the whole system rather than on individual elements. Focusing on material, energy, water and waste (MEW) process flows gives the opportunity to adopt this ecosystems view of the factory and also enables finding compatible input and output flows between components of the system, i.e. reuse of waste as a resource within the system.

Modelling of MEW process flows has been identified as an appropriate way to achieve resource flow improvement with existing manufacturing operations, facilities and buildings or for the creation of new ones by assessing different scenarios. The novelty of this modelling approach is the application of ecosystems view at factory level. In particular, it brings together existing techniques into a methodology to achieve this.

As previously discussed, a critical assumption concerns the boundaries of the system. In this research, the modelling tool is for direct use by manufacturers, and it is therefore crucial to consider their perspective on industrial activities. The control that some companies have on what is happening outside the factory is limited; this may include product design and supply chain. Thus the modelling tool focused on MEW process flows occurring on-site, i.e. gate-to-gate is used rather than product life cycle or supply chain perspective.

Beside the issue of control over elements within and outside the factory, manufacturers' knowledge about their actual emissions and waste streams is often limited. Even when data are available, data collection, understanding, modelling and analysis can be challenging: the level of granularity of data can vary for different resource types. This granularity issue can affect the level at which the data is metered (e.g. electricity at equipment level vs. at distribution bus duct level) as well as the time interval between two values (e.g., continuous recording vs. 30-min. readings vs. 3-monthly readings) and the magnitude of the flow to be taken into account (small flows add complexity to the model, but they can also have a high impact on performance, e.g., toxic waste).

To address this granularity issue, the modelling tool developed proposes an incremental model development. The model corresponds to a simplified representation of reality. Assumptions and approximations are made in order to obtain a complete model without resulting in too high a cost for the manufacturer, e.g. cost of developing a high fidelity model. Thus the main challenge in using the manufacturing ecosystem model is to determine how detailed the analysis can (or must) be, and what dimensions of performance must be included. Typically the difficulty is to represent the system at a suitable level of abstraction which is dictated by the available data and any improvements a company has already made in its manufacturing processes: as improvement activities are carried out, the data quality tends to progress and identifying opportunities for further improvements requires more detailed analysis.

8.3 Research Limitations and Findings Validity

The researcher recognises the importance of the bigger picture to optimise resource use and the need for a life cycle view on manufacturing activities to achieve environmental sustainability. The first limitation of this research concerns the scope and the boundaries set for resource flow analysis. When evaluating various improvement options, it is highly recommended to consider a wider perspective on society and Earth's systems to better account for the impact of improvements achieved within the system studied.

A second limitation of the research regarded the validity of the findings resulting from the case collection. The four conditions of design quality according to Yin (2009) are construct validity, internal validity, external validity and reliability. The construct validity can be challenging in case study research as there is a potential bias and a lack of control on the data in reported cases. However, the construct validity and reliability of the case analysis were increased by using multiple sources of evidence, creating a database to organise and categorise SMPs, establishing a protocol and chain of evidence (see Figure 2.4 in Chapter 2 Research Design), and consulting with third parties to review and use the SMPs database.

Similarly, the construct validity was ensured during the improvement hierarchy development by using multiple sources and by identifying compatibilities/commonalities in the sustainability strategies reviewed. Internal validity was addressed by using pattern-matching and cross-case synthesis as analytic techniques for identifying the improvement mechanisms of the SMPs. When the patterns observed are matching the predicted ones, the results strengthen the internal validity of the analysis (Trochim, 2006). This was the case in this analysis: the collection of SMPs revealed a number of patterns from which the researcher drew cross-case conclusions and created the tactics. Finally, the external validity and reliability issues were addressed by using replication logic in the multiple-case study (Eisenhardt, 1989). Replication logic enables the analytical generalisation of the results to other cases outside the study by developing theories explaining the recurrent patterns or regularities observed (Blaikie, 2000). In this research, the observed patterns in the SMPs were captured in the tactics to allow manufacturers to quickly replicate and adapt best practices to their own processes.

8.4 Contribution to Theory

The contribution to knowledge of this research resides in understanding the mechanisms of operational improvement for sustainable manufacturing. These mechanisms were identified from patterns in the sustainable manufacturing practices collected during the cross-sectional case study. The mechanisms of improvement were coded into generic rules (tactics) and associated logic tests. In turn, this codification allows the generalisation of industrial practices. Additionally, the practice database can help academics identify areas for future research by reviewing current state of industrial practices.

The literature review has presented various concepts and approaches for industrial sustainability which were synthesised with the improvement hierarchy. While sustainable manufacturing strategies offer insight to the overall approach taken by companies, they lack practical support for implementation: there is a gap in the literature on how to move from high-level sustainability concepts to the selection of appropriate practices. The literature also highlighted the need to systematise improvement activities in manufacturing. Thus the improvement hierarchy was used to organise the library of tactics and help prioritise improvement options for a structured and systematic identification of improvement opportunities. Consequently, the tactics library provides the link between high-level sustainability concepts and tangible actions which manufacturers can envisage in their own environment.

Finally, the library of tactics was integrated into a modelling and simulation tool via the improvement methodology which provides a structured approach to analysing manufacturing systems combining buildings and manufacturing operations analysis. The improvement methodology and tactics library have demonstrated the ability to generalise practice across industrial sector and various technological solutions. They also allowed understanding how to integrate environmental sustainability considerations in manufacturing system design and operations management.

8.5 Contribution to Practice

This research addresses the following questions from a manufacturer’s perspective: *what is sustainable manufacturing at factory level*, *how to approach sustainability in manufacturing operations* and *where to start with sustainable improvement activities*.

The research is based on extensive collection and analysis of available case studies in published literature and interaction with industry. Practices demonstrated by companies in the case collection are a key ingredient to increasing business sustainability performance and competitiveness. This research has examined the gap between strategic direction and practices for sustainability in manufacturing to extract the mechanisms behind the practices. These mechanisms were coded into generic tactics and associated logic tests to provide information on how inefficiencies and thus improvements can be identified from a manufacturer's perspective. By providing simple (and seemingly obvious) tactics, sustainability concepts become more tangible and applicable in manufacturing activities.

Additionally, this research has explored the design challenge of developing such a methodology to assist manufacturers in identifying which tactics might apply in their specific context. The improvement methodology was developed by combining the manufacturing ecosystem model (conceptual approach to industrial sustainability) and the tactics library. The combined use of resource flow modelling and tactics was tested via prototype applications and proved the ability to identify improvements through process data analysis. The improvement methodology supports manufacturers by providing a clear step-by-step guidance on how to undertake their journey towards sustainability at operational level.

Finally, the research findings have been integrated in a modelling and simulation software, developed through the THERM project, which will be commercially available to provide a supporting tool to guide manufacturers through the complex process of modelling, analysing and improving their manufacturing operations, buildings and facilities.

8.6 Recommendations for Further Research

This research has investigated sustainable manufacturing as a concept for academic research and as a set of good practices for industry. Despite an in-depth literature review and extensive data collection of industrial best practices combining a broad range of keywords and sources, the literature does not contain significant numbers and complete illustrations of sustainable practices in industry. Information is particularly deficient regarding the process of identifying inefficiencies and corresponding solutions, selection of improvement options, implementation difficulties and knowledge management about sustainability in companies.

Knowledge in the sustainable manufacturing field is fragmented but unified theories, generally accepted frameworks and models are developing. As there is a growing interest in environmental and ethical issues, sustainability is now part of the many corporate strategies. The large range of terms and concepts used in the literature can negatively impact the discussion and knowledge shared among researchers and practitioners. This was the case when collecting practices with a diverse range of terms being used in describing the activities. This issue emphasises the challenge of communication in sustainable manufacturing. As a result, there is an extensive (mis)use of terms like 'eco-efficiency', 'clean technology' or 'green energy' but there are currently no standards concerning the terminology. Thus there is a great need for standardised definitions and for a unified framework to clarify the relationship between concepts and approaches (complementary vs. overlapping vs. conflicting).

The tactics were purposefully formulated without such ambiguous expressions with a modeller and manufacturer's perspective. Thus each tactic can be used to access a group of similar sustainable manufacturing practices independently of the terminology used to describe the activities and improvements achieved.

Three areas for further work are recommended to improve the practice database, its access and knowledge transfer. First, there is a need for manufacturers and researchers to document, analyse and publish more cases on the practice and benefits of sustainable manufacturing. Current developments in the area of open innovation (Chesbrough, 2003) are demonstrating the feasibility and benefits of knowledge and experience sharing. By integrating external knowledge, new opportunities are created more quickly and efficiently. Additionally, the use of common terminology between academics and practitioners will assist in the accessibility of these cases. The practice database could be further extended to better understand the trends in various industrial sectors and provide more personalised support to companies. Secondly, search methods need to be improved to access specific examples of good practices. Easier access to practices could further support manufacturers to quickly replicate improvements achieved by other companies as well as learn how to find more innovative solutions themselves as they gain experience in applying sustainability in their operations. Finally ways of sharing the knowledge acquired through this learning process need to be further explored. This could uncover the enabling factors or conversely uncover the barriers to successful learning.

The improvement methodology developed in this research also enables manufacturers to learn how to adopt a new way of thinking and viewing their manufacturing system. Through the use of this step-by-step approach to operational improvement towards sustainable manufacturing, they can achieve a more systematic integration of environmental sustainability considerations in factory design and operation management. However, further work in sustainable performance assessment is needed to quantitatively assess benefits of various improvement options and allow more informed decision-making. This could be achieved by developing simulation and analysis capabilities to include life cycle data of the MEW process flows, to simulate the model to estimate (and predict) its environmental and economic performance, and to quantify potential benefits as well as implications for wider systems (local benefits vs. global impact).

One definite conclusion from this research is the need for more systematic application of sustainability concepts, models, strategies and principles in society in general and in industry in particular, from early design to manufacturing processes to servicing and product use and finally to end-of-life management. Sustainability must become a pervasive attitude to all human activities. Tools to support the integration of sustainability in decision-making not only need to be developed, but more importantly they need to be accessible and useable by businesses to have a real impact on their sustainability performance.

REFERENCES

Abdul Rashid, S. H., Evans, S. and Longhurst, P. (2008), "A comparison of four sustainable manufacturing strategies", *International Journal of Sustainable Engineering,* vol. 1, no. 3, pp. 214-229.

Ahlroth, S., Nilsson, M., Finnveden, G., Hjelm, O. and Hochschorner, E. (2011), "Weighting and valuation in selected environmental systems analysis tools – suggestions for further developments", *Journal of Cleaner Production,* vol. 19, no. 2-3, pp. 145-156.

Al-Homoud, M. S. (2001), "Computer-aided building energy analysis techniques", *Building and Environment,* vol. 36, no. 4, pp. 421-433.

Allenby, B. R. and Richards, D. J. (eds.) (1994), *The Greening of Industrial Ecosystems,* National Academy Press, Washington, DC.

Allwood, J. M. (2005), "What is Sustainable Manufacturing?", *Sustainable Manufacturing Seminar Series,* 16th February 2005, Cambridge University, pp. 1-32.

Alvi, A. U. and Labib, A. W. (2001), "Selecting next-generation manufacturing paradigms - An analytic hierarchy process based criticality analysis", *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture,* vol. 215, no. 12, pp. 1773-1786.

Ameling, M., Wuensch, D. and Nietzold, F. (2010), "Energy management in manufacturing based on plant integration", *APMS 2010 International Conference on Advances in Production Management Systems,* 11–13 October 2010, Como (Italy), pp. 1.

Ausubel, J. H. and Sladovich, H. E. (1989), *Technology and Environment,* National Academy of Sciences, Washington, D.C.

Ayres, R. U. (1989), "Industrial Metabolism", in Ausubel, J. H. and Sladovich, H. E. (eds.) *Technology and Environment*, National Academy Press, Washington D.C., pp. 23-49.

Ayres, R. U. and Ayres, L. W. (eds.) (2002), *A Handbook of Industrial Ecology,* Edward Elgar Publishing, Northampton, MA.

Baas, L. (1998), "Cleaner production and industrial ecosystems, a Dutch experience", *Journal of Cleaner Production,* vol. 6, no. 3-4, pp. 189-197.

Baines, T. S., Lightfoot, H. W., Evans, S., Neely, A., Greenough, R., Peppard, J., Roy, R., Shehab, E., Braganza, A., Tiwari, A., Alcock, J. R., Angus, J. P., Basti, M., Cousens, A., Irving, P., Johnson, M., Kingston, J., Lockett, H., Martinez, V., Michele, P., Tranfield, D., Walton, I. M. and Wilson, H. (2007), "State-of-the-art in product-service systems", *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture,* vol. 221, no. 10, pp. 1543-1552.

Baines, T. S., Lightfoot, H. W. and Kay, J. M. (2009), "Servitized manufacture: Practical challenges of delivering integrated products and services", *Proceedings of the Institution* *of Mechanical Engineers, Part B: Journal of Engineering Manufacture,* vol. 223, no. 9, pp. 1207-1215.

Ball, P. D., Despeisse, M., Evans, S., Greenough, R. M., Hope, S. B., Kerrigan, R., Levers, A., Lunt, P., Oates, M. R., Quincey, R., Shao, L., Waltniel, T., Wheatley, C. and Wright, A. J. (2011), "Modelling energy flows across buildings, facilities and manufacturing operations", *Proceedings of the 28th International Manufacturing Conference (IMC28),* 30 August–1 September 2011, Dublin, pp. 290-297.

Ball, P. (2010), "Industrial ecosystems", *Engineering and Technology,* vol. 5, no. 12, pp. 56-59.

Ball, P. D., Evans, S., Levers, A. and Ellison, D. (2009), "Zero carbon manufacturing facility – towards integrating material, energy, and waste process flows", *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture,* vol. 223, no. 9, pp. 1085-1096.

Batterham, R. J. (2003), "Ten years of sustainability: Where do we go from here", *Chemical Engineering Science,* vol. 58, no. 11, pp. 2167-2179.

Baumann, H. and Cowell, S. J. (1999), "An evaluative framework for conceptual and analytical approaches used in environmental management", *Greener Management International,* no. 26, pp. 109-122.

Baumann, H. and Tillman, A. (2004), *The hitch hiker's guide to LCA : an orientation in life cycle assessment methodology and application,* Studentlitteratur, Lund, Sweden.

Beamon, B. M. (1999), "Designing the green supply chain", *Logistics Information Management,* vol. 12, no. 4, pp. 332-342.

Beamon, B. M. (2008), "Sustainability and the Future of Supply Chain Management", *Operations and Supply Chain Management,* vol. 1, no. 1, pp. 4-18.

Bhamra, T. A. (2004), "Ecodesign: the search for new strategies in product development", *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture,* vol. 218, no. 5, pp. 557-569.

Bicheno, J. (2004), *The new lean toolbox : towards fast, flexible flow,* 3rd ed, PICSIE Books, Buckingham.

Bickman, L. (1987), "The functions of program theory", in Bickman, L. (ed.) *Using Program Theory in Evaluation,* Jossey-Bass, San Francisco, pp. 5-18.

Blackstone, R. (2011), *Institution of Mechanical Engineers - Energy, Environment and Sustainability, How do we achieve a sustainable lifestyle?,* available at: www.imeche.org/knowledge/industries/energy-environment-and-sustainability/news/Sustainable-Lifestyles (accessed 7 Apr 2011).

Blaikie, N. (2000), *Designing Social Research,* Polity Press, Cambridge.

Brunner, P. H. and Rechberger, H. (2004), *Practical handbook of material flow analysis*, Lewis, New York.

Bryman, A. and Bell, E. (2007; 2003), *Business research methods*, 2nd ed, Oxford University Press, Oxford.

Bunse, K., Vodicka, M., Schönsleben, P., Brülhart, M. and Ernst, F. O. (2011), "Integrating energy efficiency performance in production management - gap analysis between industrial needs and scientific literature", *Journal of Cleaner Production*, vol. 19, no. 6–7, pp. 667-679.

Carson, R. (1962), *Silent Spring*, Hamish Hamilton Ltd, London.

Chesbrough, H. W. (2003), "The era of open innovation", *MIT Sloan Management Review*, vol. 44, no. 3, pp. 35-41.

Clelland, I. J., Dean, T. J. and Douglas, T. J. (2000), "Stepping towards sustainable business: An evaluation of waste minimization practices in US manufacturing", *Interfaces*, vol. 30, no. 3, pp. 107-124.

Cleveland, C. J. and Ruth, M. (1998), "Indicators of Dematerialization and the Materials Intensity of Use", *Journal of Industrial Ecology*, vol. 2, no. 3, pp. 15-50.

Club of Rome and Meadows, D. H. (1972), *The limits to growth*, Earth Island Ltd, London.

Compressed Air Challenge (2011), *Case Studies Library*, available at: www.compressedairchallenge.org/library/index.html#Case_Studies (accessed 10 May 2011).

Cruzes, D. S. and Dyb, T. (2011), "Research synthesis in software engineering: A tertiary study", *Information and Software Technology*, vol. 53, no. 5, pp. 440-455.

Daily, B. F. and Huang, S. C. (2001), "Achieving sustainability through attention to human resource factors in environmental management", *International Journal of Operations and Production Management*, vol. 21, no. 12, pp. 1539-1552.

Davis, R. L. and Costa, J. E. (1995), "Role of ECM in bringing about pollution prevention", *International SAMPE Technical Conference*, vol. 27, pp. 328-330.

Del Brío, J. A. and Junquera, B. (2003), "A review of the literature on environmental innovation management in SMEs: Implications for public policies", *Technovation*, vol. 23, no. 12, pp. 939-948.

Despeisse, M., Ball, P. D. and Evans, S. (2013), "Strategies and Ecosystem View for Industrial Sustainability", Nee, A. Y. C., Song, B. and Ong, S. K. (eds.), in: *Re-engineering Manufacturing for Sustainability*, 17–19 April 2013, Singapore, Springer, Berlin, pp. 567.

Despeisse, M., Ball, P. D., Evans, S. and Levers, A. (2012a), "Industrial ecology at factory level – a conceptual model", *Journal of Cleaner Production*, vol. 31, no. 3-4, pp. 30-39.

Despeisse, M., Ball, P. D., Evans, S. and Levers, A. (2012b), "Industrial ecology at factory level – a prototype methodology", *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture,* vol. 226, no. 10, pp. 1648-1664.

Despeisse, M., Mbaye, F., Ball, P. D. and Levers, A. (2012c), "The emergence of sustainable manufacturing practices", *Production Planning and Control,* vol. 23, no. 5, pp. 354-376.

Despeisse, M., Ball, P. D. and Evans, S. (2011), "Identifying improvement opportunities towards sustainable manufacturing", *Proceedings of the 28th International Manufacturing Conference (IMC28),* 30 August–1 September 2011, Dublin, pp. 195-202.

Despeisse, M., Oates, M. R. and Ball, P. D. (2013), "Sustainable manufacturing tactics and cross-functional factory modelling", *Journal of Cleaner Production,* vol. 42, no. 1, pp. 31-41.

Dixon-Woods, M., Agarwal, S., Jones, D., Young, B. and Sutton, A. (2005), "Synthesising qualitative and quantitative evidence: A review of possible methods", *Journal of Health Services Research and Policy,* vol. 10, no. 1, pp. 45-53.

Dovì, V. G., Friedler, F., Huisingh, D. and Klemeš, J. J. (2009), "Cleaner energy for sustainable future", *Journal of Cleaner Production,* vol. 17, no. 10, pp. 889-895.

Ehrenfeld, J. R. and Gertler, N. (1997), "Industrial ecology in practice: The evolution of interdependence at Kalundborg", *Journal of Industrial Ecology,* vol. 1, no. 1, pp. 67-79.

Ehrlich, P. R. and Holdren, J. P. (1971), "Impact of population growth", *Science,* vol. 171, no. 3977, pp. 1212-1217.

Eisenhardt, K. M. (1989), "Building Theory from Case Study Research", *Academy of Management Journal,* vol. 14, no. 4, pp. 532-550.

Elkington, J. (1997), *Cannibals with Forks: The Triple Bottom Line of 21st Century Business,* Capstone Publishing, Oxford.

Ellen MacArthur Foundation (2013), *Towards the Circular Economy: Opportunities for the Consumer Good Sector,* Ellen MacArthur Foundation, London.

Erkman, S. (1997), "Industrial ecology: An historical view", *Journal of Cleaner Production,* vol. 5, no. 1-2, pp. 1-10.

Eurostat (2012), *Figures for the future - 20 years of sustainable development in Europe? A guide for citizens,* Publications Office of the European Union, Luxembourg.

Evans, S., Norell Bergendahl, M., Gregory, M. and Ryan, C. (2009), *Towards a sustainable industrial system,* University of Cambridge Institute for Manufacturing, Cambridge.

Figge, F., Hahn, T., Schaltegger, S. and Wagner, M. (2002), "The sustainability balanced scorecard - Linking sustainability management to business strategy", *Business Strategy and the Environment,* vol. 11, no. 5, pp. 269-284.

Finnveden, G. and Moberg, A. (2005), "Environmental systems analysis tools - An overview", *Journal of Cleaner Production,* vol. 13, no. 12, pp. 1165-1173.

Fisher, D. H. (1987), "Knowledge acquisition via incremental conceptual clustering", *Machine Learning,* vol. 2, no. 2, pp. 139-172.

Fowler, S. J. and Hope, C. (2007), "Incorporating sustainable business practices into company strategy", *Business Strategy and the Environment,* vol. 16, no. 1, pp. 26-38.

Fröhling, M., Schwaderer, F., Bartusch, H. and Schultmann, F. (2012), "A Material Flow-based Approach to Enhance Resource Efficiency in Production and Recycling Networks", *Journal of Industrial Ecology.*

Frosch, R. A. and Gallopoulos, N. E. (1989), "Strategies for Manufacturing", *Scientific American,* vol. 261, no. 3, pp. 144-152.

Gladwin, T. N., Kennelly, J. J. and Krause, T. S. (1995), "Shifting paradigms for sustainable development: Implications for management theory and research", *Academy of Management Review,* vol. 20, no. 4, pp. 874-907.

Glavič, P. and Lukman, R. (2007), "Review of sustainability terms and their definitions", *Journal of Cleaner Production,* vol. 15, no. 18, pp. 1875-1885.

Goldstein, D., Hilliard, R. and Parker, V. (2011), "Environmental performance and practice across sectors: methodology and preliminary results", *Journal of Cleaner Production,* vol. 19, no. 9-10, pp. 946-957.

Graedel, T. E. (2001), "Environmentally-benign manufacturing as a systems science", *2nd International Symposium on Environmentally Conscious Design and Inverse Manufacturing (EcoDesign '01),* 11–15 December 2001, Tokyo, pp. 876.

Graedel, T. E. (1994), "Industrial Ecology: Definition and Implementation", in Socolow, R., Andrews, C., Berkhout, F., et al (eds.) *Industrial Ecology and Global Change,* Cambridge University Press, Cambridge, pp. 23-41.

Graedel, T. E. and Howard-Grenville, J. A. (2005), *Greening the industrial facility: perspectives, approaches, and tools,* Springer, New York.

Gray, P. E. (1989), "The Paradox of Technological Development", in Ausubel, J. H. and Sladovich, H. E. (eds.) *Technology and Environment,* National Academy of Sciences, Washington, D.C., pp. 192-204.

Grubb, M. (1997), "Technologies, energy systems and the timing of CO_2 emissions abatement: An overview of economic issues", *Energy Policy,* vol. 25, no. 2, pp. 159-172.

Grübler, A. (2003), *Technology and global change,* Cambridge University Press, Cambridge.

Gupta, M. and Cawthon, G. (1996), "Managerial implications of flexible manufacturing for small/medium-sized enterprises", *Technovation,* vol. 16, no. 2, pp. 77-83.

Gutowski, T. G., Branham, M. S., Dahmus, J. B., Jones, A. J., Thiriez, A. and Sekulic, D. P. (2009), "Thermodynamic analysis of resources used in manufacturing processes", *Environmental Science and Technology,* vol. 43, no. 5, pp. 1584-1590.

Haapala, K. R., Rivera, J. L. and Sutherland, J. W. (2008), "Application of Life Cycle Assessment Tools to Sustainable Product Design and Manufacturing", *International Journal of Innovative Computing, Information and Control,* vol. 4, no. 3, pp. 577-591.

Hak, T., Moldan, B., Dahl, A. L. and International Council for Science. Scientific Committee on Problems of the Environment (2007), *Sustainability indicators : a scientific assessment,* Island Press, Washington, DC.

Hart, S. L. (1995), "A Natural-Resource-Based View of the Firm", *Academy of Management Review,* vol. 20, no. 4, pp. 986-1014.

Heilala, J., Paju, M., Montonen, J., Ruusu, R., Sorli, M., Armijo, A., Bermell-Garcia, P., Astwood, S. and Quintana, S. (2012), "Discrete Part Manufacturing Energy Efficiency Improvements with Modelling and Simulation", Emmanouilidis, C., Taisch, M. and Kiritsis, D. (eds.), in: *Competitive Manufacturing for Innovative Products andServices: Proceedings of the APMS 2012 Conference, Advances in ProductionManagement Systems,* 24–26 September 2012, Rhodes (Greece).

Heilala, J., Vatanen, S., Tonteri, H., Montonen, J., Lind, S., Johansson, B. and Stahre, J. (2008), "Simulation-based sustainable manufacturing system design", *Winter Simulation Conference Proceedings (WSC'08),* 7–10 Dec. 2008, Miami, FL, pp. 1922.

Herrmann, C. and Thiede, S. (2009), "Process chain simulation to foster energy efficiency in manufacturing", *CIRP Journal of Manufacturing Science and Technology,* vol. 1, no. 4, pp. 221-229.

Hertwich, E. G. (2005), "Consumption and the rebound effect: An industrial ecology perspective", *Journal of Industrial Ecology,* vol. 9, no. 1-2, pp. 85-98.

Hesselbach, J., Herrman, C., Detzer, R., Martin, L., Thiede, S. and Lüdemann, B. (2008), "Energy efficiency through optimized coordination of production and technical building services", *Proceedings of the 15th CIRP International Conference on Life Cycle Engineering (LCE2008),* 17–19 March 2008, Sydney (Australia), pp. 624.

Hibbard, S. (2009), "Six key factors for achieving: Sustainable Manufacturing", *Foundry Management & Technology,* vol. 137, no. 2, pp. 40.

Hibbitt, C. and Kamp-Roelands, N. (2002), "Europe's (mild) greening of corporate environmental management", *Corporate Environmental Strategy,* vol. 9, no. 2, pp. 172-182.

Holdren, J. P. and Ehrlich, P. R. (1974), "Human population and the global environment", *American Scientist,* vol. 62, no. 3, pp. 282-292.

Hope, S. (2008), "Case study: Towards zero emissions manufacturing", *Sustainable Manufacturing Summit Europe,* 19–20 November 2008, Brussels, Green Power Conferences.

Hope, S. (2011), "Sustainability in Manufacturing - towards zero emissions", *Sustainable Manufacturing Symposium,* 10 November 2011, Leicester, IET Manufacturing Network.

Hopp, W. J. and Spearman, M. L. (2008), *Factory physics*, 3rd ed, McGraw-Hill, New York.

Igartua, J. I., Garrigós, J. A. and Hervas-Oliver, J. L. (2010), "How innovation management techniques support an open innovation strategy", *Research Technology Management,* vol. 53, no. 3, pp. 41-52.

Intergovernmental Panel on Climate Change (2007), *Climate Change 2007: Synthesis Report.*

Jackson, T. (2005), "Live better by consuming less? Is there a "double dividend" in sustainable consumption?", *Journal of Industrial Ecology,* vol. 9, no. 1-2, pp. 19-36.

Jahangirian, M., Eldabi, T., Naseer, A., Stergioulas, L. K. and Young, T. (2010), "Simulation in manufacturing and business: A review", *European Journal of Operational Research,* vol. 203, no. 1, pp. 1-13.

Jawahir, I. S., Rouch, K. E., Dillon Jr., O. W., Holloway, L. and Hall, A. (2007), "Design for sustainability (DFS): New challenges in developing and implementing a curriculum for next generation design and manufacturing engineers", *International Journal of Engineering Education,* vol. 23, no. 6, pp. 1053-1064.

Jawahir, I. S., Wanigarathne, P. C. and Wang, X. (2005), "Chapter 12: Product Design and Manufacturing Processes for Sustainability", in Myer, K. (ed.) *Mechanical Engineering Handbook,* 3rd ed, John Wiley & Sons, Hoboken, NJ, pp. 414-443.

Jin, S. H. (2007), "The effectiveness of energy efficiency improvement in a developing country: Rebound effect of residential electricity use in South Korea", *Energy Policy,* vol. 35, no. 11, pp. 5622-5629.

Jovane, F., Westkämper, E. and Williams, D. (2009), *The Manufuture Road,* Springer, Berlin.

Jovane, F., Yoshikawa, H., Alting, L., Boër, C. R., Westkämper, E., Williams, D., Tseng, M., Seliger, G. and Paci, A. M. (2008), "The incoming global technological and industrial revolution towards competitive sustainable manufacturing", *CIRP Annals - Manufacturing Technology,* vol. 57, no. 2, pp. 641-659.

Kara, S., Manmek, S. and Herrmann, C. (2010), "Global manufacturing and the embodied energy of products", *CIRP Annals - Manufacturing Technology,* vol. 59, no. 1, pp. 29-32.

Kemp, R. (1994), "Technology and the transition to environmental sustainability. The problem of technological regime shifts", *Futures,* vol. 26, no. 10, pp. 1023-1046.

Kemp, R. and Soete, L. (1992), "The greening of technological progress. An evolutionary perspective", *Futures,* vol. 24, no. 5, pp. 437-457.

Keoleian, G. A. and Menerey, D. (1994), "Sustainable development by design: Review of life cycle design and related approaches", *Journal of the Air and Waste Management Association,* vol. 44, no. 5, pp. 645-668.

Kerr, I. R. (2006), "Leadership strategies for sustainable SME operation", *Business Strategy and the Environment,* vol. 15, no. 1, pp. 30-39.

Kleindorfer, P. R., Singhal, K. and Van Wassenhove, L. N. (2005), "Sustainable operations management", *Production and Operations Management,* vol. 14, no. 4, pp. 482-492.

Kolk, A. (2000), *Economics of environmental management,* Financial Times Prentice Hall, Harlow.

Kondoh, S., Nishikiori, Y. and Umeda, Y. (2005), "A Closed-loop Manufacturing System focusing on Reuse of Components", *4th International Symposium on Environmentally Conscious Design and Inverse Manufacturing (EcoDesign '05),* 12–14 December 2005, Tokyo, pp. 453.

Kumazawa, T. and Kobayashi, H. (2003), "Feasibility study on sustainable manufacturing system", *3rd International Symposium on Environmentally Conscious Design and Inverse Manufacturing (EcoDesign '03),* 8–11 December 2003, Tokyo, pp. 517.

Kuosmanen, T. and Kortelainen, M. (2005), "Measuring eco-efficiency of production with data envelopment analysis", *Journal of Industrial Ecology,* vol. 9, no. 4, pp. 59-72.

Kutz, M. (2007), *Environmentally Conscious Manufacturing,* John Wiley & Sons, Hoboken, NJ.

Labuschagne, C., Brent, A. C. and van Erck, R. P. G. (2005), "Assessing the sustainability performances of industries", *Journal of Cleaner Production,* vol. 13, no. 4, pp. 373-385.

Lakhani, M. (2007), "The need for Clean Production and Product Re-design", *Journal of Cleaner Production,* vol. 15, no. 13-14, pp. 1391-1394.

Lee, J. Y., Kang, H. S. and Do Noh, S. (2012), "Simulation-based analysis for sustainability of manufacturing system", *International Journal of Precision Engineering and Manufacturing,* vol. 13, no. 7, pp. 1221-1230.

Lélé, S. M. (1991), "Sustainable development: A critical review", *World Development,* vol. 19, no. 6, pp. 607-621.

Lifset, R. J. and Graedel, T. E. (2002), "Industrial ecology: goals and definitions", in Ayres, R. U. and Ayres, L. W. (eds.) *A Handbook of Industrial Ecology,* Edward Elgar Publishing, Northampton, MA, pp. 3-15.

London Energy Partnership (2004), *Integrating energy into new developments: Toolkit for planners, developers and consultants,* Greater London Authority, London.

Lovins, A. B., Lovins, L. H. and Hawken, P. (1999), "A road map for natural capitalism", *Harvard Business Review,* vol. 77, no. 3, pp. 145-158.

Lund, H. (2007), "Renewable energy strategies for sustainable development", *Energy*, vol. 32, no. 6, pp. 912-919.

Lunt, P. and Levers, A. (2011), *Reducing Energy Use in Aircraft Component Manufacture - Applying Best Practice in Sustainable Manufacturing*, SAE Technical Paper 2011-01-2739, SAE International.

Madsen, H. and Ulhøi, J. P. (2003), "Have trends in corporate environmental management influenced companies' competitiveness?", *Greener Management International*, no. 44, pp. 75-88.

Malthus, T.R., (1798), *An Essay on the Principle of Population*.

Marsh, G. P. (1864), *Man and Nature: Or, Physical Geography as Modified by Human Action*, C. Scribner, New York.

Matten, D. and Crane, A. (2005), "Corporate citizenship: Toward an extended theoretical conceptualization", *Academy of Management Review*, vol. 30, no. 1, pp. 166-179.

Maxwell, D. and Van der Vorst, R. (2003), "Developing sustainable products and services", *Journal of Cleaner Production*, vol. 11, no. 8 SPEC., pp. 883-895.

Mbaye, F. (2009), *Investigation of approaches for production process changes towards Sustainable Manufacturing* (MSc thesis), Cranfield University.

McDonough, W. and Braungart, M. (2002), *Cradle to cradle : remaking the way we make things*, North Point Press, New York.

Meadows, D. H. and Club of Rome (1974), *The Limits to growth : a report for the Club of Rome's project on the predicament of mankind*, Pan Books, London.

Melnyk, S. A. and Smith, R. T. (1996), *Green Manufacturing*, Society of Manufacturing Engineers, Dearborn.

Menzel, V., Smagin, J. and David, F. (2010), "Can companies profit from greener manufacturing?", *Measuring Business Excellence*, vol. 14, no. 2, pp. 22-31.

Michaloski, J. L., Shao, G., Arinez, J., Lyons, K., Leong, S. and Riddick, F. (2011), "Analysis of Sustainable Manufacturing Using Simulation for Integration of Production and Building Service", *Symposium on Simulation for Architecture and Urban Design (SimAUD 2011)*, 4–6 April 2011, Boston, MA, pp. 1.

Midilli, A., Dincer, I. and Ay, M. (2006), "Green energy strategies for sustainable development", *Energy Policy*, vol. 34, no. 18, pp. 3623-3633.

Mohanty, R. P. and Deshmukh, S. G. (1998), "Managing green productivity: Some strategic directions", *Production Planning and Control*, vol. 9, no. 7, pp. 624-633.

Mont, O. K. (2002), "Clarifying the concept of product-service system", *Journal of Cleaner Production*, vol. 10, no. 3, pp. 237-245.

Montalvo, C. (2008), "General wisdom concerning the factors affecting the adoption of cleaner technologies: a survey 1990-2007", *Journal of Cleaner Production,* vol. 16, no. 1 SUPPL. 1, pp. 7-13.

Mori, Y., Huppes, G., Udo de Haes, H. A. and Otoma, S. (2000), "Component manufacturing analysis: A simplified and rigorous LCI method for the manufacturing stage", *International Journal of Life Cycle Assessment,* vol. 5, no. 6, pp. 327-334.

Mouzon, G., Yildirim, M. B. and Twomey, J. (2007), "Operational methods for minimization of energy consumption of manufacturing equipment", *International Journal of Production Research,* vol. 45, no. 18-19, pp. 4247-4271.

Müller, K. G., Court, A. W. and Besant, C. B. (1999), "Energy Life Cycle Design: A Method", *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture,* vol. 213, no. 4, pp. 415-419.

Oates, M. R., Wright, A. J., Greenough, R. M. and Shao, L. (2011a), "Understanding Resource Flows in a Factory Environment - A Graphical Approach", Bártolo, H. e. a. (ed.), in: *Proceedings of SIM2011 conference,* 29 June–1 July 2011, Leiria (Portugal), IST Press, Lisboa, pp. 53.

Oates, M. R., Wright, A. J., Greenough, R. M. and Shao, L. (2011b), "A new modelling approach which combines energy flows in manufacturing with those in a factory building", *Proceedings of Building Simulation 2011: 12th Conference of International Building Performance Simulation Association,* 14–16 November 2011, Sydney, pp. 223.

Oldenburg, K. U. and Geiser, K. (1997), "Pollution prevention and...or industrial ecology?", *Journal of Cleaner Production,* vol. 5, no. 1-2, pp. 103-108.

Owen, J. V. (1993), "Environmentally conscious manufacturing", *Manufacturing Engineering,* vol. 111, no. 4, pp. 44-55.

Pacala, S. and Socolow, R. (2004), "Stabilization wedges: Solving the climate problem for the next 50 years with current technologies", *Science,* vol. 305, no. 5686, pp. 968-972.

Pandya, K. V. (1995), "Review of modelling techniques and tools for decision making in manufacturing management", *IEE Proceedings: Science, Measurement and Technology,* vol. 142, no. 5, pp. 371-377.

Pérez-Lombard, L., Ortiz, J., González, R. and Maestre, I. R. (2009), "A review of benchmarking, rating and labelling concepts within the framework of building energy certification schemes", *Energy and Buildings,* vol. 41, no. 3, pp. 272-278.

Pezzoli, K. (1997), "Sustainable development: A transdisciplinary overview of the literature", *Journal of Environmental Planning and Management,* vol. 40, no. 5, pp. 549-574.

Ponting, C. (2007), "The Second Great Transition", in *A new green history of the world : the environment and the collapse of great civilisations,* Rev ed, Vintage, London, pp. 265-293.

Quincey, R. J. and McLean, D. J. (2011), *Method and system for modeling energy efficient buildings using a plurality of synchronized workflows.* Integrated Environmental Solutions Ltd. Patent no. US 7,912,807 B2. Available at: www.uspto.gov/ (Accessed: 18 Apr 2012).

Rahimifard, S. and Clegg, A. J. (2007), "Aspects of sustainable design and manufacture", *International Journal of Production Research*, vol. 45, no. 18-19, pp. 4013-4019.

Rahimifard, S., Seow, Y. and Childs, T. (2010), "Minimising embodied product energy to support energy efficient manufacturing", *CIRP Annals - Manufacturing Technology*, vol. 59, no. 1, pp. 25-28.

Raymond, L., Julien, P. -., Carrière, J. -. and Lachance, R. (1996), "Managing technological change in manufacturing Smes: A multiple case analysis", *International Journal of Technology Management*, vol. 11, no. 3-4, pp. 270-285.

Reinhardt, F. L. (1999), "Bringing the environment down to earth", *Harvard Business Review*, vol. 77, no. 4, pp. 149-157.

Richards, D. J. (1994), "Environmentally conscious manufacturing", *World Class Design to Manufacture*, vol. 1, no. 3, pp. 15-22.

Richards, D. J., Allenby, B. R. and Frosch, R. A. (1994), "The Greening of Industrial Ecosystems: Overview and Perspective", in Allenby, B. R. and Richards, D. J. (eds.) *The Greening of Industrial Ecosystems*, National Academy Press, Washington, DC, pp. 1-19.

Ricoh (1994), *Concept of a Sustainable Society: The Comet Circle*, available at: www.ricoh.com/environment/management/concept.html (accessed 02/09/2011).

Ricoh (2011), *Pursuing the Ideal Society*, available at: www.ricoh.com/environment/management/earth.html (accessed 19 Oct 2011).

Robèrt, K. H. (2000), "Tools and concepts for sustainable development, how do they relate to a general framework for sustainable development, and to each other?", *Journal of Cleaner Production*, vol. 8, no. 3, pp. 243-254.

Robèrt, K. H., Schmidt-Bleek, B., Aloisi De Larderel, J., Basile, G., Jansen, J. L., Kuehr, R., Price Thomas, P., Suzuki, M., Hawken, P. and Wackernagel, M. (2002), "Strategic sustainable development - Selection, design and synergies of applied tools", *Journal of Cleaner Production*, vol. 10, no. 3, pp. 197-214.

Robèrt, K. H. (1996), *The Natural Step.*

Robinson, J. (2004), "Squaring the circle? Some thoughts on the idea of sustainable development", *Ecological Economics*, vol. 48, no. 4, pp. 369-384.

Rusinko, A. (2007), "Green Manufacturing: An Evaluation of Environmentally Sustainable Manufacturing Practices and Their Impact on Competitive Outcomes", *IEEE Transactions on Engineering Management*, vol. 54, no. 3, pp. 445-454.

Salvato, J. A., Nemerow, N. L. and Agardy, F. J. (2003), *Environmental Engineering,* 5th ed, John Wiley & Sons, Hoboken, NJ.

Sandén, B. A. and Azar, C. (2005), "Near-term technology policies for long-term climate targets - Economy wide versus technology specific approaches", *Energy Policy,* vol. 33, no. 12, pp. 1557-1576.

Sangle, S. (2011), "Adoption of cleaner technology for climate proactivity: A technology-firm-stakeholder framework", *Business Strategy and the Environment,* vol. 20, no. 6, pp. 365-378.

Sarkis, J. (1995), "Manufacturing strategy and environmental consciousness", *Technovation,* vol. 15, no. 2, pp. 79-97.

Sarkis, J. (1998), "Evaluating environmentally conscious business practices", *European Journal of Operational Research,* vol. 107, no. 1, pp. 159-174.

Sarkis, J. (2001), "Manufacturing's role in corporate environmental sustainability: Concerns for the new millennium", *International Journal of Operations and Production Management,* vol. 21, no. 5-6, pp. 666-686.

Sarkis, J. (2003), "A strategic decision framework for green supply chain management", *Journal of Cleaner Production,* vol. 11, no. 4, pp. 397-409.

Sarkis, J. and Rasheed, A. (1995), "Greening the Manufacturing Function", *Business Horizons,* vol. 38, no. 5, pp. 17-27.

Seliger, G., Karl, H. and Weber, H. (1997), "Cooperative design, manufacturing and assembly of complex products", *CIRP Annals - Manufacturing Technology,* vol. 46, no. 1, pp. 67-X14.

Seliger, G. (2001), "Product innovation - Industrial approach", *CIRP Annals - Manufacturing Technology,* vol. 50, no. 2, pp. 425-443.

Seliger, G. (2007), *Sustainability in manufacturing: recovery of resources in product and material cycles,* Springer, Berlin.

Seliger, G., Kim, H. J., Kernbaum, S. and Zettl, M. (2008), "Approaches to sustainable manufacturing", *International Journal of Sustainable Manufacturing,* vol. 1, no. 1-2, pp. 58-77.

Seliger, G. and Zettl, M. (2008), "Modularization as an enabler for cycle economy", *CIRP Annals - Manufacturing Technology,* vol. 57, no. 1, pp. 133-136.

Seuring, S. and Müller, M. (2008), "From a literature review to a conceptual framework for sustainable supply chain management", *Journal of Cleaner Production,* vol. 16, no. 15, pp. 1699-1710.

Shewhart, W. A. (1939), *Statistical Method from the Viewpoint of Quality Control,* Washington, DC.

Sidgwick, H. (1883), *Principles of Political Economy*, Macmillan and Co., London.

Smil, V. (2003), *Energy at the crossroads : global perspectives and uncertainties*, MIT Press, Cambridge, Mass.

Srivastava, S. K. (2007), "Green supply-chain management: A state-of-the-art literature review", *International Journal of Management Reviews*, vol. 9, no. 1, pp. 53-80.

Stern, D. I., Common, M. S. and Barbier, E. B. (1996), "Economic growth and environmental degradation: The environmental Kuznets curve and sustainable development", *World Development*, vol. 24, no. 7, pp. 1151-1160.

Tan, A. R., Matzen, D., McAloone, T. C. and Evans, S. (2010), "Strategies for designing and developing services for manufacturing firms", *CIRP Journal of Manufacturing Science and Technology*, vol. 3, no. 2, pp. 90-97.

THERM Project (2011), *THrough-life Energy and Resource Modelling (THERM)*, available at: www.therm-project.org/ (accessed 15 July 2011).

Thiede, S., Herrmann, C. and Kara, S. (2011), "State of research and an innovative approach for simulating energy flows of manufacturing systems", *Glocalized Solutions for Sustainability in Manufacturing - Proceedings of the 18th CIRP International Conference on Life Cycle Engineering*, pp. 335.

Thomas, J. and Harden, A. (2008), "Methods for the thematic synthesis of qualitative research in systematic reviews", *BMC Medical Research Methodology*, vol. 8.

Trochim, W. M. K. (2006), *www.socialresearchmethods.net/kb/*, available at: www.socialresearchmethods.net/kb/ (accessed 09-04-2012).

Vachon, S. and Klassen, R. D. (2008), "Environmental management and manufacturing performance: The role of collaboration in the supply chain", *International Journal of Production Economics*, vol. 111, no. 2, pp. 299-315.

Van Berkel, R., Willems, E. and Lafleur, M. (1997), "The relationship between cleaner production and industrial ecology", *Journal of Industrial Ecology*, vol. 1, no. 1, pp. 51-66.

Van de Ven, Andrew H. (2007), *Engaged scholarship*, Oxford University Press, Oxford.

Wackernagel, M. and Rees, W. E. (1996), *Our ecological footprint : reducing human impact on the earth*, New Society, Gabriola Island, B.C.

Welford, R. (2003), "Beyond systems: A vision for corporate environmental management for the future", *International Journal of Environment and Sustainable Development*, vol. 2, no. 2, pp. 162-173.

Westkämper, E. (2002), "Platform for the integration of assembly, disassembly and life cycle management", *CIRP Annals - Manufacturing Technology*, vol. 51, no. 1, pp. 33-36.

Westkämper, E., Alting, L. and Arndt, G. (2001), "Life cycle management and assessment: Approaches and visions towards sustainable manufacturing", *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture,* vol. 215, no. 5, pp. 599-626.

Westkämper, E., Feldmann, K., Reinhart, G. and Seliger, G. (1999), "Integrated development of assembly and disassembly", *CIRP Annals - Manufacturing Technology,* vol. 48, no. 2, pp. 557-565.

Womack, J. P. and Jones, D. T. (1996), *Lean Thinking: Banish Waste and Create Wealth in Your Corporation,* Simon and Schuster, New York.

World Commission on Environment and Development (WCED) (1987), *Our common future,* Oxford University Press, Oxford.

Wu, C. (2008), "Knowledge creation in a supply chain", *Supply Chain Management,* vol. 13, no. 3, pp. 241-250.

Yin, R. K. (2009, 1994), *Case Study Research: Design and Methods,* 4th ed, SAGE, Beverly Hills, CA.

APPENDIX – SUSTAINABLE MANUFACTURING PRACTICE DATABASE

#	Sustainable Manufacturing practice	Tactic	Sector	Reference
1	Replace old compressors with new high efficiency ones	A42	Steel industry	www.compressedairchallenge.org/library/casestudies/weirtons.pdf
2	Addition of air treatment equipment	A43		
3	Leak reparation	A31		
4	Renovation of the pumping system	A42	Automotive glass	www.osti.gov/glass/Best%20Practices%20Documents/Assessment%20Case%20Studies/Millwater%20pumping%20system.pdf
5	Replace old run/modulation sequencer with a programmable logic control (PLC) system: centralize the control of all 5 compressors, maintain adequate pressure differential between the compressor pressure settings, and sequence them more efficiently; system linked to the pressure/flow controllers to obtain accurate demand signals.	A42	Metal forging	www.compressedairchallenge.org/library/casestudies/moddr.pdf
6	Install 2 pressure/flow controllers (in forge shop and in die shop): pressure/flow controllers to provide stable header pressure of 100 psig in forge shop, to provide air at 85 psig in die shop.	A35		
7	Add 2 receivers: 7,500 gallons of storage.	A43		
8	Modify piping distribution system to connect the dryers before the storage, and opened the valves in the forge shop header.	A42		
9	Install an additional dryer.	A43		
10	Replace dirty filters.	A31		
11	Implement leak detection/repair campaign: replace worn point-of-use components (air leak), plant personnel training about compressed air system dynamics and the importance of managing leaks.	A31		
12	Replaced old, malfunctioning condensate drains on compressors and dryers with 8 pneumatic drains.	A42		
13	Purchase and install a dedicated 40-hp compressor for weekend packaging operations and some die shop functions, so that the 200-hp compressor would not be used for those tasks.	A43		
14	In-house chip reclamation	A24	Automotive aluminium	American Council for an Energy-efficient Economy: www.aceee.org/P2/p2cases.htm
15	Advanced furnace with better recovery and fewer pollutants than the off-site melting process	A43		

#	Sustainable Manufacturing practice	Tactic	Sector	Reference
16	Upgrade and computerize equipment	A34	Forging industry	
17	New furnaces with higher efficiency	A42		
18	Anaerobic treatment of organic nutrients in wastewater to produce biogas (mostly methane)	A24	Brewery	
19	Energy capture in low pressure steam from 7 thermo-mechanical pulping refiner lines by using 2 mechanical vapor recompression heat pumps	A24	Pulp and paper	
20	Partnership: use Chaparrel waste as inputs for highway construction and cement industry	A24	Steel industry	
21	High efficiency lamps, ballasts and motors and insulated hot tanks	A42	Metal industry	
22	Reduced solvent evaporation	A31		
23	Replacing floor dry with absorbent pads and wringer reducing plant waste	A44		
24	Newer material improve heat transfer and increase productivity	A42	Fertilizer	
25	More efficient units reduce heat and steam demand (water and fuel consumption)	A42		
26	Testing of a membrane-based technology (full-scale prototype) to recover and reuse discharged furnace gas, Avoid installation of expensive pollution control equipment	A24	Automotive and heavy equipment	
27	Infrared Drying: Replacement on the first production line	A43	Iron casting	
28	Water recirculation	A24	Key retainer device	
29	Cleaning using an oil skimmer, Elimination of chemical treatment	A42		
30	Installation of variable-speed drives (VSDs)	A42	Textile	
31	Development and commercialization of a new technology	A42	Printing industry	
32	Paper and plastics recycling	A24		
33	Reduced ink waste, closed-loop ink-jet supply and printer solvent recovery system	A24		
34	Reparation of wooden pallets	A24		
35	Change of from 3 8-hour to 2 12-hour shifts	A12		
36	Use processing and alloying procedures that enable appropriate structures and strength to be developed in thin section ductile iron castings. Evaluate the environmental implications of substituting this new material for existing ferrous and non-ferrous materials used in automotive castings.	A22	Casting	Loughborough University: wolftest.lboro.ac.uk/research/manufacturing-technology/SMART/sustainable-projects-students.htm
37	Introduction of innovative ultrasonic assisted cutting technology	A42	Machining	
38	Installation of bare steam pipes	A43	Food sector: preserved food industry	El-Haggar, S. (2007), Sustainable Industrial Design and Waste Management:
39	Replacement of leaking steam valves	A31		
40	Replacement of defective steam traps	A31		

#	**Sustainable Manufacturing practice**	**Tactic**	**Sector**	**Reference**
41	Installation of temperature controller on sterilizers	A34		Cradle-to-cradle for Sustainable Development, 1st ed, Elsevier Academic Press, California, USA.
42	Recovery of steam condensate	A15		
43	Improving boiler efficiency by reducing the air to fuel ratio	A32		
44	Installation of water meters	A34		
45	Installation of hose nozzles	A43		
46	Improving the water collection system on the juice line	A24		
47	Installation of cooling tower for the bottled juice line	A43		
48	Chip and trash recovery system => good housekeeping technique	A15	Food sector: sugar beet manufacturing	
49	Diffusion and juice purification => better process control	A35		
50	Heat exchange and evaporation => better process control	A35		
51	Sugar and purity control: modification of the sugar purity management steps, lowering the purity of liquor and reviewing the crystallisation management	A32		
52	Unknown losses: Improving maintenance to stop leakages and improving operations to provide steady state condition => good housekeeping technique	A31		
53	Improved housekeeping	A31	Food sector: milk production	
54	Rationalisation of milk packaging	A13		
55	Milk refrigeration efficiency increased	A42		
56	Reuse of the whey	A24		
57	Upgraded boiler	A31		
58	Restored softening unit	A31		
59	Collection of used oil	A15		
60	Milk tank level controls, Food quality valves	A35		
61	Substitution of the sodium sulfide with glucose	A22	Textile sector	
62	Substitution of the dichromate with sodium perborate	A22		
63	Trials with variable concentrations, rates at which chemicals were added, temperature, number and timing of washes.	A32	Textile sector	
64	More expensive chemicals were phased out and replaced with ammonium persulfate and Egyptol.	A22		
65	Trials to combine scour and bleach processes more efficiently and to phase out the use of sodium hypochlorite in bleaching.	A32		

#	**Sustainable Manufacturing practice**	**Tactic**	**Sector**	**Reference**
66	Hydrogen peroxide used to substitute the sodium hypochlorite in the full bleaching process.	A22		
67	Storage facilities improved	A31	Textile sector	
68	Material substitution	A22		
69	Optimisation of chemical usage	A34		
70	Collection of steam condensate (equipment modification: condensate stored in a tank)	A15		
71	Reuse of steam condensate	A24		
72	Equipment modification: condensate re-circulated to the process water feed lines by means of pumps and piping network	A24		
73	Upgraded insulation of steam and hot water network (better process control)	A31		
74	Counter current flow (process control)	A35		
75	Installation of automatic shut-off valves in bleaching ranges	A42		
76	Recycling of final washing water in the bleaching ranges (on-site recycling, process range)	A24		
77	Source (oil) reduction thanks to good housekeeping	A31	Oil and soap sector	
78	Source (oil) reduction thanks to preventive maintenance through upgrading oil loading and unloading procedures (improved procedural instructions, supervision of transfer operations)	A31		
79	Installation of 3 gravity oil separators manufactured by the factory	A43		
80	Segregation of the cooling water, vacuum water and process water from one another in parallel with rehabilitation of the two existing cooling towers	A31		
81	Use of liquid caustic soda in the refinery unit	A22	Oil and soap sector	
82	Upgraded system network in the steam unit	A31		
83	Recovery of broken seeds in the receiving unit	A31		
84	Reuse of fines in the preparation unit	A24		
85	Preventive maintenance program in all the factory units	A31		
86	Implement alternatives to conventional spray gun systems	A43	Wood furniture sector	
87	Flush equipment first with dirty solvent before final cleaning with virgin solvent	A24		
88	Use cleanup solvents in the formulation of paint	A22		
89	Minimisation of the use of water to where it is needed	A13		
90	Improvement of the insulation of the furnace, so there will not be any heat dissipation	A31		

#	**Sustainable Manufacturing practice**	**Tactic**	**Sector**	**Reference**
91	Installation of an oil fog system in the steamer controlled cooling line thus reducing oil consumption	A43		
92	Improvement of the transportation of oil without any leaks or spills during the process	A31		
93	Reforming of the hydrodynamic system from the ration pump to the various pumps	A43		
94	Replacement of the hydrodynamic system pipes to reduce oil losses	A42		
95	Installation of a waste oil connector in the coil collection oil station to reduce oil discharges	A43		
96	On-site recycling in cement production process (most efficient in wet process); need more research to optimise percentage of bypass dust recycled without affecting cement properties	A24	Cement industry	
97	Production of tiles/bricks/interlocks blended cements	A15		
98	Enhancing the production of road pavement layers	A31		
99	Production of safe organic compost by stabilising municipal waste water sludge	A24		
100	Production of glass and ceramic glass	A15		
101	Better scrap management in the storage area	A25	Aluminium foundries industry	
102	Arrange molds near the smelters away from traffic	A25		
103	Stack the products more loosely	A25		
104	Cutting scrap should be collected and compacted	A15		
105	Cut the big blocks into smaller pieces before smelting	A22		
106	Reduce the size of the slabs during the pouring phase in order to reduce the scrap	A22		
107	Change the square slabs into round slabs to reduce scrap	A22		
108	Upgrading the smelting furnace	A31		
109	Upgrading the annealing oven	A31		
110	Upgrading the rolling machine	A31		
111	Upgrading the spinning machine	A31		
112	Upgrading the polishing processes	A31		
113	Mud-cutting separation	A15	Drill cuttings, Petroleum sector	
114	Treatment (On-site indirect thermal desorption, distillation, solvent extraction, combustion, stabilisation and biological treatment)	A15		
115	Reuse/Recycle opportunities: cuttings could be reused in construction and landscaping for example in concrete products, coastal defenses, land reclamation, pipe beddings, landfill cells, roads and pavements, top soil admix and fill materials.	A24		

#	Sustainable Manufacturing practice	Tactic	Sector	Reference
116	Solid fuel using briquetting technology	A22	Sugarcane Industry	
117	Solid fuel using briquetting technology	A24		
118	Gasification of bagasse-cachaza, biogas	A22		
119	Gasification of bagasse-cachaza, biogas	A24		
120	Traditional fossil fuels: natural gas	A22		
121	Processing Basic oxygen furnace (BOF) slag	A15	Iron and steel industry	
122	Dry slag granulation	A24		
123	Ground granulated blast furnace (BF) slag can be used in concrete	A15		
124	Composite pavement base material made of steel-making slag and blast furnace slag	A15		
125	Use of BF and BOF slags in road paving as a base, sub-base, and surface layers	A15		
126	Use of Electric Arc Furnace (EAF) slags as a road-paving base material and as coarse aggregate for producing concrete suitable for applications such as wave breakers, sidewalk blocks and profiles, and manhole covers	A15		
127	Use of BF, BOF and EAF slags as coarse aggregate replacements in the production of building materials such as cement masonry units and paving stone interlock	A15		
128	Modify the charging, blowing, and waste gas exhaustion system to minimize dust formation	A35		
129	Analyse dust composition produced during different phases of furnace operations	A34		
130	and, if appropriate, segregate the recovered dust	A15		
131	Reuse of the EAF Dust using micro-pelletizing (method used to turn steel plant dust into a valuable raw material): dust mixed with lime as a binder and pelletize to produce a fine granular form	A24		
132	Replacement of phenolic resin by furanic resin in the molding system and core shop, by cold-curing with an organic-base catalyser	A22	Casting	Seliger, G. (2007), Sustainability in Manufacturing: Recovery of Resources in Product and Material Cycles, 1st ed, Springer Berlin Heidelberg, Berlin, Germany
133	Recovery of the used sand (containing furanic acid) by a mechanical process at room temperature	A24		
134	The company also intends to develop a form of using the foundry sand as a construction material, thereby completely avoiding its disposal in landfill	A15		
135	Re-evaluation of the cutting oils/emulsions used in each stages of the processes and classification into 8 families of oils	A15	Automotive industry	
136	Implementation of a selective collection of the metal chips impregnated with oils/ emulsions based on the classification	A15		

#	Sustainable Manufacturing practice	Tactic	Sector	Reference
137	Oils/emulsions are separated and stored in containers: they are physicochemically analysed to check and possibly adjust the technical conditions.	A15		
138	After this determination, they're reused in the cutting process from which they originated or passed on for use in equipment.	A24		
139	The company plans to install a cutting oil regeneration facility in order to extend its reuse of regenerated oils	A24		
140	Reduce water consumption and preserve natural resources while simultaneously reducing water-related costs: filtration and reuse of treated effluent in industrial process and toilets	A43	Electrical goods industry	
141	Studies are also in progress to implement a water treatment system by reverse osmosis or water demineralisation to allow the reuse of 100% of the treated effluent in processes that require better quality reused water	A24		
142	Experiments carried out in-house indicated that the CO_2 used for cooling the parts could be replaced successfully by compressed air. This replacement was put into effect without requiring any equipment or process changes.	A22	Motor vehicle part manufacturing industry	
143	Upgrade paint booth	A31		
144	Recycling of powder at a 95% rate	A24		
145	Automatic spray guns increased efficiency	A31		
146	Change pre-curing to electric infrared	A42		
147	Virtual engine Development: Incorporating computer simulation, advanced analysis tools and leading measurement technology to plan, predict & analyse the outcome of engine development processes	A34		
148	Determine high volume manufacturing processes based on materials and functions, Weight trade-offs between 1st time quality & capability for remanufacturing	A34	Automotive industry	International Conference on Sustainable Manufacturing 23-24 Sept. 2008 (OECD, Rochester, NY, USA): www.oecd.org/document/48/0,3343,en_2649_34173_40953456_1_1_1_1,00.html
149	Replacement of rotary by modular type (electronic component mounting machines)	A42	Electrical goods industry	International Conference on Sustainable Manufacturing 23-24 Sept. 2008 (OECD,
150	Replacement of hydraulic by motorised type (molding machines)	A42		
151	Increase the number of Plasma Display Panels (PDP) produced from a single substrate	A32		

#	Sustainable Manufacturing practice	Tactic	Sector	Reference
152	Finer semiconductor processing on large diametre wafers	A32		Rochester, NY, USA): www.oecd.org/document/48/0,3343,en_2649_34173_40953456_1_1_1_1,00.html
153	Elimination of mineral spirits to preclean parts	A21	Casting industry	Park, E., Enander, R. and Barnett, S. M. (2002), "Pollution prevention in a zinc die casting company: a 10-year case study", Journal of Cleaner Production, vol. 10, no. 1, pp. 93-99.
154	Elimination of hypochloric acid used to settle & remove sludge	A21		
155	Elimination of a 100000 litres/month sewer discharge of metal-bearing wastewater	A41		
156	Recovery of zinc-metal for off-site recycling	A24		
157	Recycling of an aqueous based soap	A24		
158	Environmentally Friendly, High performance substitute Materials for Manufacturing and Facilities	A22	Aerospace sector	Dhooge, P., Glass, S. and Nimitz, J. (1998), Successful Environmentally Friendly, high Performance Substitute Materials for Manufacturing and Facilities, SAE technical Paper 981872, Society of Automotive Engineers, USA.
159	Development of low production new products: low weights, high grade non wooden	A44	Pulp and paper	International Conference on Cleaner Production (Sept 2001, Beijing, China): www.chinacp.org.cn/eng/cpconfer/iccp01/iccp13.html
160	Feedstock substitution (fibre regeneration, energy reuse, high-grade non-wood feedstock base building)	A24		
161	Technologies improvement (Dry & wet feedstock preparation, continuous/time delay cooking, continuous multi-stage bleaching)	A13		
162	Set up individual responsibilities to operators for shut-off practices	A33	Automotive industry	Business in the community: www.bitc.org.uk/resources/case_studies/afe1259_ford.html
163	Optimisation of all high usage equipment & machines engineering to reduce: coolant flow, extracted air volumes, compressed air requirements, chilled air requirements	A31		
164	Use of "high lubricity" vegetable oil metal working fluids	A22		
165	Implementation of a briquetting process for oily ferrous sludges that are usually changed into pucks so that they can be recycled & used as feedstock in the cement industry	A15		
166	Visual controls and displays throughout the plant	A34	Automotive industry	Business in the community: www.bitc.org.uk/resources/case_studies/afe256envtoyota.htm
167	Introduction of a centrifuge to reduce the water content of the sludge (previously major waste to landfill)	A43		
168	And then pump the water back into the paint ponds for reuse	A24		

#	Sustainable Manufacturing practice	Tactic	Sector	Reference
169	The remaining dried residue can be used in cement production	A15		
170	Agreement of the supply chain with Toyota goals thanks to Toyota's "Duty of Care Audits" that ensure that once waste has left the plant, it is dealt in the correct way	A15		
171	Piping of the 2800 megawatts of heat generated by the data centre to the local public swimming pool	A15	Computer industry	Turton, S. (2008), "IBM cools data centre with swimming pool", PC Pro: computing in the real world, accessed on: 15 june 2009 available at: www.pcpro.co.uk/news/184539 /ibm-cools-data-centre-with-swimming-pool.html
172	New stainless control valves for precise control of water flow	A42	Microelectronic devices industry	American Council for an Energy-efficient Economy: www.aceee.org/P2/p2cases.htm
173	New manifold added to the Reverse Osmosis pump converting it to a more efficient two-stage pump	A43		
174	High surface area Reverse Osmosis membranes added	A43		
175	Existing PVC piping replaced with industrial, water production piping	A42		
176	By automating the process, low-cost precision pumping systems allow a small volume of dyebath chemicals to be reused for numerous dyeing operations	A31	Carpet industry	American Council for an Energy-efficient Economy: www.aceee.org/P2/p2cases.htm
177	Innovative monitoring instruments can analyze the dyebath and communicate results to a computer which calculates the amount of chemicals that need to be added for the next dyeing operation	A34		
178	Energy is saved by reducing the need to reheat dyebaths, eliminating the energy used to produce additional dyes, chemicals and water, and reducing energy needed to treat wastewater	A35		
179	Less energy intensive approach: cristaliser, condenser and cooling unit evaporator put under pressure,	A44	Chemical industry	American Council for an Energy-efficient Economy: www.aceee.org/P2/p2cases.htm
180	No intermediate liquid heat-transfer medium, No buffer vessels, Fewer and smaller pumps, piping, and valves,	A41		
181	Lower temperature differentials, Less space requirement	A32		
182	The system uses recirculated water to pasteurize and cool food products, using the heat capacity and thermal integrity of water to control temperatures reliably	A24	Food industry	American Council for an Energy-efficient Economy: www.aceee.org/P2/p2cases.htm
183	Recirculating water reduced the need to heat and cool the water, cutting gas and electricity used by the boiler and fans.	A24		

#	**Sustainable Manufacturing practice**	**Tactic**	**Sector**	**Reference**
184	Benchmarking	A34	Dry cleaning	ALTHAM, W., 2007. Benchmarking to trigger cleaner production in small businesses: drycleaning case study. Journal of Cleaner Production, 15(8-9), 798-813.
185	Good housekeeping	A31		
186	Regional synergy to energy recovery from flue gases	A24	Industrial area	BEERS, D.V. and BISWAS, W.K., 2008. A regional synergy approach to energy recovery: The case of the Kwinana industrial area, Western Australia. Energy Conversion and Management, 49(11), 3051-3062.
187	Improve air quality through material resource substitution	A22	Cement	KABIR, G. and MADUGU, A.I., 2010. Assessment of environmental impact on air quality by cement industry and mitigating measures: A case study. Environmental monitoring and assessment, 160(1-4), 91-99.
188	Improve air quality through higher energy efficiency technologies	A42		
189	Shift from coal-based oxygen steel production to electricity-based production	A22	Steel industry	Christian Lutz, Bernd Meyer, Carsten Nathani, Joachim Schleich, 2005, Endogenous technological change and emissions: the case of the German steel industry, Energy Policy 33(9), 1143-1154
190	Improvements in end-of-pipe waste-water treatment technologies	A31	Water resource protection	CHOUR, V., 2001. Water resources protection today: End-of-pipe technology and cleaner production. Case study of the Czech Odra River watershed.

#	Sustainable Manufacturing practice	Tactic	Sector	Reference
191	Long-term monitoring data	A34	Sugar cane	GUNKEL, G., KOSMOL, J., SOBRAL, M., ROHN, H., MONTENEGRO, S. and AURELIANO, J., 2007. Sugar cane industry as a source of water pollution - Case study on the situation in Ipojuca river, Pernambuco, Brazil. Water, air, and soil pollution, 180(1-4), 261-269.
192	Water conservation through implementation of ultra-filtration and reverse osmosis system with recourse to recycling of effluent	A24	Textile	NANDY, T., MANEKAR, P., DHODAPKAR, R., POPHALI, G. and DEVOTTA, S., 2007. Water conservation through implementation of ultrafiltration and reverse osmosis system with recourse to recycling of effluent in textile industry-A case study. Resources, Conservation and Recycling, 51(1), 64-77.
193	Improve quality of discharge water through analysis of wastewater effluent composition generated by a petrochemical industry and a treatment system	A15	Refining and petrochemicals	SOJI ADEYINKA, J. and RIM-RUKEH, A., 1999. Effect of hydrogen peroxide on industrial waste water effluents: A case study of Warri refining and petrochemical industry. Environmental monitoring and assessment, 59(3), 249-256.
194	Assessment of a wastewater treatment process	A35		
195	Good housekeeping	A31	Leather	STOOP, M.L.M., 2003. Water management of production systems optimised by
196	Waste treatment (hair-saving techniques, effluents, chromium sludge and bio-sludge)	A15		
197	Rethink process layout (all wet processes located at one location)	A45		

#	**Sustainable Manufacturing practice**	**Tactic**	**Sector**	**Reference**
198	Reuse wastewater	A24		environmentally oriented integral chain management: Case study of leather manufacturing in developing countries. Technovation, 23(3), 265-278.
199	Good housekeeping and regular maintenance	A31	Beet sugar	ŽBONTAR ZVER, L. and GLAVIČ, P., 2005. Water minimization in process industries: Case study in beet sugar plant. Resources, Conservation and Recycling, 43(2), 133-145.
200	Division of wastewater streams with different quality	A15		
201	Simplified procedure for wastewater regeneration, reuse of steam condensate in boiler house and of some wastewater in systems that allow such level of water contamination	A24		
202	Substitution of solvent paint by high solid paint	A22	Forklift manufacturing	KIM, J., PARK, K., HWANG, Y. and PARK, I., 2010. Sustainable manufacturing: A case study of the forklift painting process. International Journal of Production Research, 48(10), 3061-3078.
203	More efficient technology to reduce the total basic power consumption	A42	Sustainable machining	Herrmann, C., Zein, A., Thiede, S., Bergmann, L., and Bock, R. (2008). Bringing sustainable manufacturing into practice – the machine tool case. In: Sustainable Manufacturing VI: Global Conference on Sustainable Product Development and Life Cycle Engineering, Pusan, Korea.
204	Reduce energy consumption during non-production time by organizational and technical measures (stand-by-mode)	A11		
205	Dry machining (sufficiency)	A44		
206	Minimum quantity lubrication (efficiency)	A32		
207	Alternative solutions, fluids with minimum environmental impact (LCA to avoid shift of burden to another LC phase)	A22		
208	Resource-preserving filter technology	A43		
209	Extractive oil removal	A15		
210	Substitution of processes by sustainable process alternatives	A44		
211	Minimising oven door	A42	Glass industry	Energy management: A two-day training course for managers in Central and
212	Optimising oven temperature	A34		
213	Optimizing cooling fan	A34		

#	**Sustainable Manufacturing practice**	**Tactic**	**Sector**	**Reference**
214	Turning off ventilation fans once buses had left the depot.	A34	Garage	Eastern Europe. Produced by Forbait for The Directorate-General for Energy (DGXVII) of The Commission of the European Communities. Thermie.
215	Reduce space heating at night.	A34		
216	Use of radiant heat to warm mechanics and staff.	A43		
217	Boiler maintenance (burner service & clean nozzle)	A31		
218	Boiler maintenance (reduction of excess air, CO_2 content adjusted to 2 and smoke number reduced to 2)	A34		
219	Measure heating demand / requirements	A34	Chemical industry	
220	2 (out of 15) heaters were disconnected	A41		
221	Flash steam recovery from the rest 13 heaters.	A24		
222	Steam and condensate return pipeline insulation repaired and improved	A31	Dairy plant	
223	Process tanks/vessels insulated	A31		
224	One major steam main shut off during normal operation	A11		
225	Regulating load so that oven was always full	A13		
226	Installing heat exchanger between oven exhaust and fresh air inlet.	A43		
227	New continuous rotating cooked installed	A42	Processing of animal waste products	
228	Variable speed drives incorporated, to automatically control feed and discharge rates.	A32		
229	The four processing stages were ‘decoupled’ by adding buffer storage between each stage.	A13		
230	Automatic controls to only permit one other process to operate at the same time as cooker.	A32		
231	14 variable speed drives installed, to vary fan and pump speeds according to thermostat and humidistat signals.	A43		
232	Timer/contactor control fitted	A35		[4] EC (2007), Best practices, in: BESS - Benchmarking and Energy management Schemes in SMEs
233	Hundreds of leaks in both systems identified and repaired.	A31	Plumbing and pipe fittings	
234	140 ball valves fitted to air lines.	A35		
235	1(out of 3) compressors was disconnected	A41		
236	Refrigeration diagnosis expert system installed.	A43	Brewery	
237	Replace chillers with new.	A42	Brewery	
238	Cool at two separate temperatures.	A32		

#	Sustainable Manufacturing practice	Tactic	Sector	Reference
239	Instrument calibration.	A31	Chemical industry	
240	System modification	A32		
241	Introduction of CHP – Combined Heat and Power process	A43	Textile	
242	Installation of solar-thermal collectors	A43	Meat process	
243	Installation of heat recovery unit	A24	Textile	
244	Optimization of cooling compressors by using VSD - variable speed driver	A32	Dairy plant	
245	Re-calculate the required capacity of the steam boiler at different time periods based on production schedule.	A32	Paper	
246	Replacement of the existing steam generation units with other types of boiler having lower operation and maintenance costs.	A42		
247	Fuel switch project from natural gas to woodchips	A22		
248	Installation of solar thermal system for the pre-heating of the steam boiler feed water	A43	Diary plant	
249	Installation of automatic boiler blow-down heat recovery for the pre-heating of the steam boiler feed water	A43		
250	Introduction of CHP – Combined Heat and Power process	A43	Diary plant	
251	Introduce biogas to the energy mix	A22		
252	Installation of new boiler house and steam distribution system	A42	Diary plant	
253	Installation of heat recovery units on the baking oven	A24	Bakery	
254	Hybrid Heat pump for elevated recovery temperature	A24	Diary plant	
255	1. Reduce excess combustion air to minimum	A35		[4] EC (2007), Horizontal Energy Efficiency Measurement List, in: BESS - Benchmarking and Energy management Schemes in SMEs
256	1a. CO2/O2 measurement	A34		
257	2. Maximise completeness of combustion	A35		
258	2a. Soot/CO measurement	A34		
259	3. Maintain boiler cleanliness (soot/scale)	A31		
260	3a. Monitor for rise in flue gas temperature	A34		
261	4. Repair (replace) boiler insulation	A31		
262	4a. Periodic inspection of boiler insulation condition.	A31		
263	5. Insulate feedwater tank / cover tank	A31		
264	5a. Check possible feedwater temperature losses	A34		

#	Sustainable Manufacturing practice	Tactic	Sector	Reference
265	6. Insulate condensate return lines	A31		
266	6a. Check possible heat loss from condensate return lines.	A34		
267	7. Optimise quality of make-up water and feedwater	A32		
268	7a. Monitor quality of make-up water and feedwater: hardness, acidity, O2.	A34		
269	8. Minimise blowdown	A32		
270	8a. Monitor concentration of dissolved solids in boiler water.	A34		
271	8b. Improve blowdown controls	A35		
272	9. Maintain nozzles, grates, fuel supply pressure/temperature at manufacturers' specifications	A31		
273	9a. Ensure specifications are available and in use.	A35		
274	9b. Regular check and resetting/maintenance.	A31		
275	10. Maximise combustion air temperature	A32		
276	10a. Draw air from highest point in boiler house.	A22		
277	11. Reduce steam pressure where it exceed system/process requirements.	A32		
278	11a. Check system/process needs; adjust controls.	A32		
279	12. Use duct for intake of warmer combustion air	A22		
280	12a. Install duct from combustion air intake to higher parts of room.	A22		
281	13. Install an automated gas leakage detector.	A34		
282	14. Repair leaks in steam pipework.	A31		
283	1. For rapidly varying demand, convert one or more boilers to live accumulator (buffer tank).	A42		
284	1a. Monitor/evaluate demand change patterns.	A34		
285	2. Alter controls to 'High-Low-Off' or 'modulating-Low-Off'	A35		
286	2a. Monitor/evaluate demand change patterns.	A35		
287	3. Install flash steam heat recovery	A24		
288	3a. Consider in large capacity situations with high (continuous/frequent) blowdown.	A35		
289	4. Improve combustion controls.	A35		
290	4a. Provide adequate heat input to meet demand.	A32		
291	4b. Minimise fuel/pollution.	A32		

#	**Sustainable Manufacturing practice**	**Tactic**	**Sector**	**Reference**
292	4c. Protect personnel/equipment.	-		
293	5. Waste heat recovery	A24		
294	5a. Economizer	A43		
295	5b. Air heater (recuperator)?	A43		
296	6. Install boiler blowdown heat recovery.	A24		
297	6a. Consider in large capacity situations with high (continuous/frequent) blowdown.	A35		
298	7. Use process integration	A24		
299	7a. Couple process units that have significantly different heat requirements (i.e. low-pressure steam leaving a high-pressure steam consuming production process can be used for a process requiring low-pressure steam).	A24		
300	1. Repair/replace faulty insulation	A31		
301	1a. Pipework insulation / especially around valves.	A31		
302	2. Repair inefficient steam traps/drains. valve spindles etc.	A31		
303	2a. Regular checks for leaks throughout the system.	A31		
304	3. Insert valves to isolate 'periodic-use' items in system.	A35		
305	3a. Check system for periodic (e.g. seasonal, nightly) items (e.g. space heaters).	A35		
306	4. Remove/isolate 'dead-legs' and redundant pipework	A21		
307	4a. Check for dead-legs and redundant piping.	A21		
308	1. Replace steam traps/drains with more efficient designs.	A42		
309	1a. Monitor efficiency of, and heat losses from existing traps.	A34		
310	2. Replace or increase insulation	A31		
311	2a. Check existing insulation; estimate heat losses in system.	A31		
312	3. Maximise condensate returns.	A32		
313	3a. Measure 'discarded' heat from condensate.	A34		
314	4. Redesign system to minimise pipe runs.	A25		
315	5. Generation pressure reduction.	A13		
316	1. Plant insulation	A31		
317	2. Local burner efficiency	A43		
318	3. Maximise heat transfer rate	A24		

#	Sustainable Manufacturing practice	Tactic	Sector	Reference
319	4. Improve controls (e.g. thermostats)	A35		
320	5. Consider alternative energy source	A22		
321	6. Ensure plant at high load factor	A13		
322	7. Eliminate uneconomic 'hot standby' periods	A11		
323	8. Recycle waste heat to process	A24		
324	9. Recover heat, for use elsewhere	A24		
325	10. Train all staff to operate manual controls and to watch for energy saving opportunities.	A35		
326	1. Use heat only when area is occupied	A11		
327	2. Set thermostats to minimum for comfort	A32		
328	3. Minimise loss of hot air	A31		
329	4. Clean and effective heaters	A31		
330	5. Maintain pipe insulation in unheated areas	A31		
331	6. Check condensate traps	A31		
332	7. Vent air from hot water systems	A24		
333	8. Time switches	A35		
334	9. Manual controls where appropriate	A35		
335	1. Install more/more efficient thermostats	A35		
336	2. Use motorized valves to divide building into different zones	A35		
337	3. Air curtains	A43		
338	4. Change energy source	A22		
339	5. Change heating system / where:	A42		
340	· If good insulation and high ventilation, then use radiant heat	A42		
341	· If poor insulation and low ventilation, then use convective heat	A42		
342	6. Improve building insulation	A42		
343	1. Try to ensure that motor capacity is not more than 25% in excess of full load.	A32		
344	2. Install motor controllers (voltage, power factor and fixed speed controllers).	A35		
345	3. Build in 'soft-start' facilities.	A32		
346	4. Install variable speed drives	A42		
347	5. Install high efficiency motors	A42		

#	**Sustainable Manufacturing practice**	**Tactic**	**Sector**	**Reference**
348	1. Switch off whenever possible.	A11		
349	2a. Install low-cost solenoid valves on air supply lines to individual machines.	A43		
350	2b. Switch off compressed air supply as soon as machine is switched off.	A33		
351	3. Clean air intake filters regularly	A31		
352	4. Use lowest possible operating pressure. Reduce pressure locally if possible.	A32		
353	5. Use lowest air intake temperature possible.	A32		
354	6. Fit 2-speed motors.	A43		
355	7. Fix leaks	A31		
356	8. Check on correct pressure setting regularly.	A34		
357	1. Fit a small (jockey) compressor to meet off-peak demand.	A43		
358	2. Duct air intake to ensure coolest possible.	A43		
359	3. Fit air flow and kWh meters to monitor power and air use.	A34		
360	4. Install modern controls on multi-compressor installations.	A35		
361	5. Fit a standard heat recovery unit.	A24		
362	6. Air pre-cooling.	A24		
363	7. If some users are using low pressure air (2.5 / 3 bar), install two separate systems.	A32		
364	8. Use frequency control for compressor.	A35		
365	9. Use an individual compressed air supply for special applications.	A43		
366	10. Replace pneumatic tools be electrical tools	A22		
367	1. Switch off whenever possible.	A11		
368	2. Regular maintenance is necessary to maintain pump efficiency and prevent breakdown, especially when the vacuum-space contains condensing vapours;	A31		
369	3. Fix leaks	A31		
370	1. Fit a standard heat recovery unit.	A24		
371	2. Use a central vacuum system with several delivery points	A13		
372	1. Group refrigeration cells according to temperature.	A45		
373	2. Use an integrated plant layout / optimise use of evaporators or condensers (i.e. remove obstacles)	A45		
374	3. Limit energy losses through open doors	A31		

#	Sustainable Manufacturing practice	Tactic	Sector	Reference
375	1. Switch off lights, fans, pumps. etc., when not required.	A11		
376	2. Repair damaged insulation/seals.	A31		
377	3. Check for refrigerant contamination.	A31		
378	4. Check for scaling on condenser and evaporator surfaces.	A34		
379	5. (Multi-compressor systems); set controls to activate minimum number of compressors.	A35		
380	6. Monitor timing and duration of defrost cycles. Defrost on demand rather than at fixed intervals.	A34		
381	7. Use load rescheduling (e.g. cool at night) where maximum-demand tariffs are in operation.	A13		
382	8. Minimise cooling space by installing removable plastic screens or panels or by filling cooling space with polystyrene foam blocks	A32		
383	9. Switch off evaporator fans when compressor is off	A11		
384	10. Regulate condenser pressure (and therefore temperature)	A32		
385	11. Delayed start-up of compressors. Initially, only start-up of ventilation.	A13		
386	12. Increase the evaporation temperature.	A32		
387	1. Install kWh meters and instrumentation to monitor equipment and cold room.	A34		
388	2. Install an energy management system which analyses operation of the whole refrigeration system.	A35		
389	3. Use effective insulation and sealing.	A31		
390	4. Install efficient electronic expansion valves. Avoid 'head pressure control' where possible.	A43		
391	6. Recovery of waste heat at the condenser	A24		
392	7. Automatic bleeding of refrigerant to remove any penetrated air	A31		
393	8. Install frequency control (i.e. VRF) on chiller compressor.	A35		
394	9. Install high efficiency or 2-rev electromotor on evaporation fan	A43		
395	10. Build a cooled front space for refrigeration units.	A45		
396	11. Use hot refrigerant gas from the compressor for the initial stages of the defrosting cycle.	A24		
397	12. Use excess heat from other production processes for the production of cooling using adsorption/absorption cooling.	A24		

#	Sustainable Manufacturing practice	Tactic	Sector	Reference
398	1. Use the most efficient lamps consistent with required illumination levels and colour rendering.	A42		
399	2. Use the light output from lamps efficiently.	A32		
400	3. Maintain lamps and fixtures clear of light-blocking dust and dirt.	A31		
401	4. Switch off lights where lighting is not needed.	A11		
402	5. Consider automatic control of lighting (time clocks and/or photo cells).	A35		
403	6. Make the best use of daylight.	A41		
404	7. Avoid the absorption of light by the surroundings (light-coloured wall, ceilings, and floors).	A45		
405	8. Replace lamps which have exceeded their rated life.	A31		
406	9. Use 'switch-off' and 'save-it' stickers as a tool of good housekeeping.	A33		
407	10. Consider new technologies in order to reduce installation cost, such as infrared switching.	A35		
408	11. Divide the lighting system of a large space into several independent lighting groups.	A13		
409	12. Use presence detection switches	A35		
410	13. Use a lighting system that is continuously variable (e.g. high-frequency fluorescent lighting).	A35		
411	1.Thermal insulation of floor	A43		
412	2.Thermal insulation of walls	A43		
413	3.Thermal insulation of roof	A43		
414	4. Use of double-glazed or solar shading glass windows	A42		
415	1. Use a weather dependent control to regulate the temperature of the boiler water in relation to the outside temperature.	A35		
416	2. Install an advanced timer for the boiler operation schedule.	A43		
417	3. Insulate pipework	A43		
418	4. Insulate hot water storage tanks	A43		
419	1. Divide large interior spaces into smaller areas.	A32		
420	2. Use radiation heating in cases where large ventilation rates are required.	A42		
421	3. Use displacement ventilation where the heated indoor areas are higher than 6 meters.	A42		
422	1. Heat recovery of exhaust air using a rotary wheel.	A24		

#	Sustainable Manufacturing practice	Tactic	Sector	Reference
423	2. Reduce the amount of ventilation air as much as possible by the installation of:	A32		
424	· Timer switch;	A11		
425	· Occupancy sensor	A35		
426	· Air quality;	A35		
427	· Frequency control on the fan motor	A35		
428	3. Prevent infiltration through door openings with:	A32		
429	· Thermal insulation	A43		
430	· Draught curtains	A43		
431	· Air cushion	A43		
432	· Automatic door	A43		
433	· Slip door	A43		
434	· Rubber seal between door and doorpost instead of brushes or no sealing.	A43		
435	1. Use local exhaust ventilation systems. The purpose of a local exhaust system is to remove the contaminants (dust, fume, vapour etc.) at the source.	A42		
436	2. Some options for improving the efficiency of exhaust systems are:	A32		
437	· Frequency control on the electromotor of the fan	A35		
438	· Close exhaust points that are not in use.	A33		
439	· Start up the exhaust system with all exhaust points closed.	A12		
440	1. Use thermal energy storage systems (i.e. ice banks)	A43		
441	2. Use shading devices for windows.	A43		
442	Tune the large furnace burners to get proper air-fuel ratio – 2% or less O2 in flue gases.	A32	Products related to traffic safety	Energy Savings Assessment (ESA) Summary Report For 3M – Brownwood, TX Plant (Nov. 7-9, 2005) apps1.eere.energy.gov/industry/saveenergynow/partners/pdfs/esa-001-1.pdf
443	Install proper controls (temperature control or other type close loop control – feed rate control) for the large furnaces.	A35		
444	Adjust boiler burners to maintain approximately 2% O2 in exhaust gases regularly at average operating conditions	A31		
445	using manual adjustment or tuning the burners periodically (i.e. twice a year) and by operating the boilers at as close to full load as possible to maintain efficiency of the boilers	A31		
446	Purchase basic instrumentation such as an oxygen/combustible analyzer to allow frequent measurement of flue gas analysis for the heating systems.	A34		
447	Install O2/CO trim control for boiler	A34		

#	Sustainable Manufacturing practice	Tactic	Sector	Reference
448	Install a stack recuperator to heat air (or water) and recover heat from furnace exhaust gases. Use air for dryer and water for make-up air heating.	A24		
449	Install an economizer or hot water/air heater for boilers to recover heat from the boiler flue gases	A24		
450	Water heating by using thermal oxidizer exhaust gas heat (available at approximately 350 deg. F. and 125,000 scfm flow rate) and use water for make-up air heating and/or humidification of air in winter months.	A24		
451	Use of exhaust gas heat (if clean) from the small furnaces to preheat air or water.	A24		
452	Improve insulation for the large furnaces	A31		
453	Consider use of hot water to supply heat to a thermally activated absorption cooling system. This would eliminate use of electricity for chillers.	A24		
454	Use desiccant dryer to dehumidify make-up air and eliminate use of chilled water to reduce humidity in air prior to reheating. This will also reduce steam requirement for reheating the air.	A24		
455	Preheat feed material for the furnaces by using hot air from the recuperator (use furnace exhaust gas heat to heat the air)	A24		
456	Consider use of oxy-fuel burners for the large furnaces	A42		
457	Consider use of carbon bed system to concentrate vapors in press exhaust air	A42		
458	During the harsh winters, the chiller units on all of the company's presses run on a "free" cooling chiller. In cold months, water is pumped to the a refrigeration unit—where it is cooled naturally. Roof—instead of a refrigeration unit—where it is cooled naturally.	A44	Printing	Energy Matters, winter 2011, vol.1, iss.2 page5. www1.eere.energy.gov/industry/bestpractices/energymatters/pdfs/energy_matters_winter_2011.pdf
459	Brew kettle heats thin sheets of wort—the liquid extracted from the mashing process during the brewing of beer—rather than the whole kettle at once.	A44	Brewery	Energy Matters, winter 2011, vol.1, iss.2 page6. www1.eere.energy.gov/industry/bestpractices/energymatters/pdfs/energy_matters_winter_2011.pdf
460	Use of methane produced by process water treatment to fuel a combined heat and power engine—or co-gen—which creates electricity and heat for the brewery.	A24		
461	Developing a new technology to monitor the color of polymers—a key ingredient in plastic manufacturing—during the high-heat, high-pressure extrusion process. Currently, if polymers are the wrong color, they are often recycled back through the extrusion process. Although this does save the material, the redundancy of the process uses extra energy and increases carbon emissions.	A24	Polymers	Energy Matters, winter 2011, vol.1, iss.2 page7. www1.eere.energy.gov/industry/bestpractices/energymatters/pdfs/energy_matters_winter_2011.pdf

#	Sustainable Manufacturing practice	Tactic	Sector	Reference
462	Replace all of the high pressure sodium (HPS) fixtures installed in its facility with T8 fluorescent bulbs.	A42	Aluminium foundry	Eck Industries, Inc. Realizes Savings Through Smarter Lighting Solutions www1.eere.energy.gov/industry/saveenergynow/pdfs/eck_industries_case_study.pdf
463	Installation of variable frequency drives	A43	Pulp and paper	Flambeau River Papers Makes a Comeback With a Revised Energy Strategy www1.eere.energy.gov/industry/saveenergynow/pdfs/case_study_flambeau.pdf
464	New pumps, lighting upgrades	A31		
465	The plant has also implemented heat recovery systems through the hood exhaust in the mill and biomass dryer and stack in the boiler house.	A24		
466	Wastewater treatment system has been installed in the mill.	A15		
467	No longer use coal as a base for its electricity replace with other fuels such as pulp, bark, tree tops, branches, logging residue, and damaged wood as feedstocks for biomass. The company will also utilize wood tar from liquid smoke, red liquor, and industrial pellets.	A22		
468	These feedstocks will be used to make ethanol at the plant's bio-refinery, it will produce alternative fuel and paraffnic wax.	A24		
469	The biofuel will also supply the mill with 150 psi steam for paper-making along with residual hot water.	A22		
470	upgrade natural gas burners	A31	Casting	Harrison Steel www1.eere.energy.gov/industry/saveenergynow/pdfs/harrison_steel_success_story.pdf
471	Fix around 100 air leaks	A31		
472	Variable speed drives project for well pumps	A43		
473	Install more efficient lighting	A42	Heating, ventilation and air conditioning (HVAC) systems and services	Ingersoll Rand Discovers Hidden Savings with a Three-Tiered Energy Audit Model www1.eere.energy.gov/industry/saveenergynow/pdfs/ingersoll_rand_success_story.pdf
474	Replace HVAC units, upgrade compressors	A31		
475	Using occupancy sensors	A35		
476	Using more efficient pumps	A42		
477	Training	-		
478	Installed variable-frequency drives	A43	Automotive	Nissan Showcases the Results of an Energy-Wise Corporate Culture www1.eere.energy.gov/industry/saveenergynow/pdfs/nissan_case_study.pdf Smyrna Paint Plant Energy
479	Reduced number of air compressors	A41		
480	Sub-metering & monitoring	A34		
481	Upgraded and replaced chillers	A31		
482	Upgraded lighting and controls	A31		

#	Sustainable Manufacturing practice	Tactic	Sector	Reference
483	Air recirculation	A24		Reduction Strategy www1. eere.energy.gov/industry/saveenergynow/pdfs/smyrna_paint_plant_energy_reducation_strategy.pdf
484	Air Leak repair	A31		
485	Space Temps set to seasonal Set-Points	A32		
486	Hourly KW Alarm monitoring	A35		
487	Determine the efficiency of your steam generation system (based on steam output/fuel input).	A34		Steam Generation through cogeneration applications, boiler controls, and water treatment - Opportunities for Improvements www1.eere. energy.gov/industry/bestpractices/steamgenerate.html
488	Determine how much steam you use, and how much it costs to generate this steam. Steam generation needs to be measured with accurate, well maintained and calibrated flow measurement devices and reconciled by a rigorous steam balance. The steam balance should be done on a regular basis to confirm that the flow measurements are good.	A35		
489	Optimize excess air in your boiler to increase steam generation efficiency. An often stated rule of thumb is that boiler efficiency can be increased by 1% for each 15% reduction in excess air or 40° F reduction in stack gas temperature. Good measurements of fuel flow and air flows are required to do this as well as good stack gas analysis.	A31		
490	Maintain clean fire-side and water-side boiler heat transfer surfaces. A good deposit control program is necessary to do this.	A31		
491	Optimize boiler blowdown to reduce Total Dissolved Solids (TDS) in the boiler system. Work closely with your boiler feed water additives vendor to do this.	A31		
492	Optimize your boiler control system to optimize steam generation efficiency. Before you do this, make sure that the logic diagrams actually reflect what is wired into the system and that all the components of this system make sense and work.	A31		
493	Ensure that an effective water treatment system is in place. Work closely with your boiler feed water additives vendor to do this.	A15		
494	Properly select, size, and maintain your distribution system steam traps.	A32		Steam Distribution through checking steam leaks, installing insulation and proper steam trap maintenance - Opportunities for Improvements www1.eere. energy.gov/industry/bestpractices/steamdistub.html
495	Insulate all distribution system pipes, flanges, and valves.	A31		
496	Ensure that steam mains are properly laid out, sized, adequately drained, and adequately air vented.	A35		
497	Ensure that Distribution System piping is correctly sized to produce the appropriate system pressure drops.	A35		
498	Ensure that distribution system piping is adequately supported, guided, and anchored, and that appropriate allowances are made for pipe expansion at operating temperatures.	A35		

#	Sustainable Manufacturing practice	Tactic	Sector	Reference
499	Understand how much steam is used per unit of product produced. You can use this information to compare with other information—within your company and by your competition—to determine where there might be opportunities for improvement of your steam operations.	A34		Steam End Use through heat exchanger maintenance - Opportunities for Improvements www1.eere.energy.gov/industry/bestpractices/steamenduse.html
500	Select, size, and maintain steam traps for specific end use applications.	A31		
501	Blowdown of non-condensables from condensing equipment is critical. If non-condensables are not removed from condensing applications, the condensing equipment will quickly cease to function. The rule of thumb is that for every 1% of non-condensables there is in steam, the heat transfer coefficient decreases by 10%.	A31		
502	Identify how much condensate you presently recover and return to the boiler system. Determine if you can increase the amount of condensate that you return - cost savings can result from energy savings and from water treatment cost savings.	A34		Steam Recovery through condensate return - Opportunities for Improvements www1.eere.energy.gov/industry/bestpractices/steamrecoverycondensate.html
503	Ensure that the condensate piping is adequately sized. Condensate piping has to accommodate two-phase flow B liquid and vapor. The vapor portion of the condensate stream is more voluminous than the liquid portion. In general, condensate piping must be sized to handle the flash and blow-through steam rather than just the liquid portion. Condensate piping that is sized for the liquid portion only will be grossly undersized.	A35		
504	Ensure that your condensate return piping, flanges, and valves are properly insulated.	A35		
505	Identify if it is possible to return hot condensate to a flash recovery system, so that you can use the flash steam to supplement low-pressure steam needs.	A24		
506	New burners and controls installed on two boilers	A42	Potato processing	J. R. Simplot: Burner Upgrade Project Improves Performance and Saves Energy at a Large Food Processing Plant www1.eere.energy.gov/industry/bestpractices/pdfs/simplot.pdf
507	1 out of 3 boilers removed	A41		
508	New faceplates mounted on each boiler front before the new burners could be installed	A42		
509	New combustion air fans, flue gas recirculation ducts, flue gas oxygen analyzers, and boiler control systems with oxygen trim systems were installed on each boiler.	A42		
510	Install a steam flow-meter in the facility and calculate your steam generation cost. Compare this with the benchmark value.	A34		Clean Boiler Waterside Heat Transfer Surfaces www1.eere.energy.gov/industry/bestpractices/pdfs/steam7_surfaces.pdf
511	Pretreating of boiler makeup water (using water softeners, demineralizers, and reverse osmosis to remove scale-forming minerals)	A22		
512	Injecting chemicals into the boiler feedwater	A23		
513	Adopting proper boiler blowdown practices	A24		

#	**Sustainable Manufacturing practice**	**Tactic**	**Sector**	**Reference**
514	Determine your boiler capacity, average steam production, combustion efficiency, stack gas temperature, annual hours of operation, and annual fuel consumption.	A34		Consider Installing a Condensing Economizer www1.eere.energy.gov/industry/bestpractices/pdfs/steam_26a.pdf
515	Obtain an installed cost quotation for and determine the cost-effectiveness of a condensing economizer. Ensure that system changes are evaluated and modifications are included in the design (e.g., mist eliminator, additional water treatment, heat exchangers). Simple paybacks for condensing economizer projects are often less than two years.	A34		
516	Determine how much steam enthalpy, pressure and temperature are required at the header downstream from your boiler.	A32		Consider Installing High-Pressure Boilers with Backpressure Turbine-Generators www1.eere.energy.gov/industry/bestpractices/pdfs/steam22_backpressure.pdf
517	Develop steam flow/duration curves for your boiler. (Remember that electrical generation will follow your steam load or process heating requirements).	A34		
518	Use the tools provided in this fact sheet to estimate your electricity generation potential and to determine savings from purchasing and installing a high-pressure boiler plus a backpressure turbine-generator	A34		
519	Consider installing turbulators in natural gas or oil-fired boilers with two- or three-pass firetube boiler tubes if your stack gas temperature is 100°F or more above your steam or hot water temperature.	A43		Consider Installing Turbulators on Two- and Three- Pass Firetube Boilers www1.eere.energy.gov/industry/bestpractices/pdfs/steam25_firetube_boilers.pdf
520	Replace electric motors with steam turbine drives if your facility.	A42		Consider Steam Turbine Drives for Rotating Equipment www1.eere.energy.gov/industry/bestpractices/pdfs/steam21_rotating_equip.pdf
521	Determine your boiler capacity, combustion efficiency, stack gas temperature, annual hours of operation, and annual fuel consumption.	A34		Considerations When Selecting a Condensing Economizer www1.eere.energy.gov/industry/bestpractices/pdfs/steam_26b.pdf
522	Identify in-plant uses for low-temperature heated water (plant space heating, boiler makeup water heating, preheating, or process requirements).	A34		
523	Installing a condensing economizer. Determine the cost-effectiveness of a condensing economizer, ensuring that system changes are evaluated and modifications are included in the design (e.g., mist eliminator, heat exchangers). Simple paybacks for condensing economizer projects are often less than 2 years.	A43		

#	Sustainable Manufacturing practice	Tactic	Sector	Reference
524	Evaporation and heat losses can be reduced by lowering the liquid temperature, reducing the exposed liquid area, minimizing flow of air over the tank, or installing an insulated cover.	A32		
525	Deaerator steam requirements should be reexamined following the retrofit of steam distribution system, condensate return, or heat recovery energy conservation measures.	A32		Deaerators in Industrial Steam Systems www1.eere.energy.gov/industry/bestpractices/pdfs/steam18_steam_systems.pdf
526	Install continuous dissolved oxygen monitoring devices to aid in identifying operating practices that result in poor oxygen removal.	A34		
527	Determine the potential for high-pressure condensate flashing by completing a plant survey that: • Identifies all sources of high-pressure condensate. • Determines condensate flow and duration, as well as the heat recovery potential due to flashed steam production. • Identifies compatible uses for low-pressure steam. • Estimates the cost effectiveness of installing appropriate heat-recovery devices and interconnecting piping.	A34		Flash High-Pressure Condensate to Regenerate Low-Pressure Steam www1.eere.energy.gov/industry/bestpractices/pdfs/steam12_lowpressure_steam.pdf
528	Steam traps are tested primarily to determine whether they are functioning properly and not allowing live steam to blow through. • Establish a program for regular systematic inspection, testing, and repair of steam traps. • Include a reporting mechanism to ensure thoroughness and to provide a means of documenting energy and dollar savings.	A34		Inspect and Repair Steam Traps www1.eere.energy.gov/industry/bestpractices/pdfs/steam1_traps.pdf
529	Determine the energy savings and cost-effectiveness from using a heat exchanger to recover energy from the blowdown and preheat boiler makeup water. blowdown heat-recovery systems may be economical for boilers with blowdown rates as low as 500 lb/hr.	A43		Install an Automatic Blowdown Control System www1.eere.energy.gov/manufacturing/tech_deployment/pdfs/steam23_control_system.pdf
530	Conduct a survey of your steam distribution system to identify locations where removable and reusable insulation covers can be used.	A34		Install Removable Insulation on Valves and Fittings www1.eere.energy.gov/industry/bestpractices/pdfs/steam17_valves_fittings.pdf
531	Use removable insulation on components requiring periodic inspections or repair.	A31		
532	Boilers often operate at excess air levels higher than the optimum. Periodically monitor flue gas composition and tune your boilers to maintain excess air at optimum levels.	A13		Improve Your Boiler's Combustion Efficiency www1.eere.energy.gov/industry/bestpractices/pdfs/steam4_boiler_efficiency.pdf
533	Consider an automatic blowdown control system	A43		

#	Sustainable Manufacturing practice	Tactic	Sector	Reference
534	Determine the efficiency and operating cost of each of your boilers and adopt a control strategy for maximizing overall efficiency of multiple boiler operations.	A34		Minimize Boiler Short Cycling Losses www1.eere.energy.gov/industry/bestpractices/pdfs/steam16_cycling_losses.pdf
535	Avoid short cycling by purchasing a burner with a high turndown ratio or by adding a small boiler to your boiler house to provide better flexibility and high efficiency at all loads.	A42		
536	If there is a continuous blowdown system in place, consider installing a heat recovery system.	A43		Recover Heat from Boiler Blowdown www1.eere.energy.gov/industry/bestpractices/pdfs/steam10_boiler_blowdown.pdf
537	If there is a non-continuous blowdown system, then consider the option of converting it to a continuous blowdown system coupled with heat recovery.	A13		
538	Consider installing backpressure turbogenerators in parallel with PRVs when purchasing new boilers or if your boiler operates at a pressure of 150 psig or greater. • Develop a current steam balance and actual process pressure requirements for your plant. • Develop steam flow/duration curves for each PRV station. • Determine plant electricity, fuel cost, and operating voltage. • Consider either one centralized or multiple turbogenerators at PRV stations.	A43		Replace Pressure-Reducing Valves with Backpressure Turbogenerators www1.eere.energy.gov/industry/bestpractices/pdfs/steam20_turbogenerators.pdf
539	Install a condensate return system	A43		Return Condensate to the Boiler www1.eere.energy.gov/industry/bestpractices/pdfs/steam8_boiler.pdf
540	Repair steam distribution and condensate return system leaks.	A31		
541	Insulate condensate return system piping to conserve heat and protect personnel.	A43		
542	Perform burner maintenance and tune your boiler.	A31		Upgrade Boilers with Energy-Efficient Burners www1.eere.energy.gov/industry/bestpractices/pdfs/steam24_burners.pdf
543	Conduct combustion-efficiency tests at full- and part-load conditions.	A34		
544	If excess oxygen exceeds 3%, or combustion efficiency values are low, consider modernizing the fuel/air control system to include solid-state sensors and controls without linkage. Also consider installing improved process controls, an oxygen trim system, or a new energy- efficient burner.	A35		
545	A new energy-efficient burner should also be considered if repair costs become excessive, reliability becomes an issue, energy savings are guaranteed, and/or utility energy conservation rebates are available.	A42		
546	Install a smaller burner on a boiler that is oversized relative to its steam load.	A42		

#	Sustainable Manufacturing practice	Tactic	Sector	Reference
547	Investigate thermocompressors where significant venting of low-pressure steam occurs, higher-pressure motive steam is available, and a modest pressure boost could convert waste steam to useful steam. Examine waste recovery potential by determining: – Flow rate and pressure of vented steam – Flow rate and pressure for sources of motive steam – Process or heating needs that can be met by boosting the pressure and temperature of vented steam – Equipment size and motive to suction steam ratio – Annual energy savings and installation costs of selected device	A34		Use Steam Jet Ejectors or Thermocompressors to Reduce Venting of Low-Pressure Steam www1.eere.energy.gov/industry/bestpractices/pdfs/steam29_use_steam.pdf
548	Consider vacuum jet ejectors in situations where: – Mild vacuum conditions —1 to 3 psig below ambient —would help the process operation – Waste steam at pressures greater than 15 psig are vented to the atmosphere	A43		
549	A vapor recompression project analysis consists of matching recovered waste heat with the need for low-pressure steam for process or space heating. To perform this analysis: • Conduct a plant audit to identify sources of low-pressure waste steam. • Estimate the heat recovery potential. • Inventory all steam-utilizing equipment and list pressure requirements, energy consumption, and patterns of use. • Estimate the cost-effectiveness of installing recompression equipment and connecting piping.	A24		Use Vapor Recompression to Recover Low-Pressure Waste Steam www1.eere.energy.gov/industry/bestpractices/pdfs/steam11_waste_steam.pdf
550	Inspect vent pipes of receiver tanks and deaerators for excessive flash steam plumes.	A31		Use a Vent Condenser to Recover Flash Steam Energy www1.eere.energy.gov/industry/bestpractices/pdfs/39315.pdf
551	Eliminate flash steam energy loss with a vent condenser.	A31		
552	Minimize Boiler Combustion Loss by Optimizing Excess Air	A31	Pulp and paper, chemical manufacturing, and petroleum refining industries	Steam System Opportunity Assessment www1.eere.energy.gov/industry/bestpractices/pdfs/steam_assess_mainreport.pdf Appendices www1.eere.energy.gov/industry/bestpractices/pdfs/steam_assess_appendices.pdf
553	Repair or Replace Burner Parts	A31		
554	Install Feedwater Economizers	A43		
555	Install Combustion Air Preheaters	A43		
556	Clean Boiler Heat Transfer Surfaces	A31		
557	Install Continuous Blowdown Heat Recovery	A43		
558	Establish the Correct Vent Rate for the Deaerator	A32		
559	Repair Steam Leaks	A31		
560	Isolate Steam from Unused Lines	A25		
561	Use High-Pressure Condensate to Generate Low-Pressure Steam	A24		
562	Implement a Combined Heat and Power (Cogeneration)	A43		

#	Sustainable Manufacturing practice	Tactic	Sector	Reference
563	Exchangers were redesigned to give more heat transfer overall.	A42		Celanese Chemicals Clear Lake Plant Energy Projects Assessment and Implementation www1.eere.energy.gov/industry/bestpractices/pdfs/sd01art8.pdf
564	Introduce Heat Exchanger	A43		
565	Use a Single Incinerator Instead of Two	A41		
566	Run 1a Distillation Tower Only Part- Time	A13		
567	Optimize Tower Operation	A11		
568	Improve Process Control of Large Air Compressor	A35		
569	Eliminate Hot Standby for Utilities Boilers	A13		
570	Eliminating hot standby for spare turbines	A13		
571	Shutting down outmoded process systems	A41		
572	Optimizing pump impeller usage	A13		
573	Changed tower operation to use lower-pressure steam when possible	A13		
574	Reduce steam header pressure.	A32		Best Practices Steam Resources and Tools: “Old” News is “New” News! www1.eere.energy.gov/industry/bestpractices/pdfs/sd01art1.pdf
575	Reduce steam pressure in distillation columns.	A32		
576	Install additional steam traps on drum oven.	A43		
577	Improve steam trap maintenance program.	A31		
578	Replace faulty compressor turbine, and reconfigure steam and cooling systems.	A31		
579	Insulate steam lines, replace faulty steam traps.	A31		
580	Replace existing steam boiler system, improve plant heat recovery.	A42		
581	Rebuild and upgrade steam turbine.	A42		
582	Install new boiler combustion controls, replace more than 90% of system steam traps.	A42		
583	Steam Demand Reduction	A12		Best Practices in Steam System Management www1.eere.energy.gov/industry/bestpractices/pdfs/sd01art2.pdf
584	Boiler Tune-Up	A31		
585	Use of backpressure turbines for power production	A42		Tools to Boost Steam System Efficiency www1.eere.energy.gov/industry/bestpractices/pdfs/steam_tools.pdf
586	Recovery of thermal energy from waste-water streams	A24		
587	Replacement of missing insulation on piping systems	A31		
588	Reduction of steam leaks resulting from failed steam traps and pipes	A31		

#	Sustainable Manufacturing practice	Tactic	Sector	Reference
589	Adjust burner air to fuel ratios. To get the most efficient performance out of fuel-fired furnaces, ovens, and boilers: 1. Determine the best level of excess air for operating your equipment. 2. Set your combustion ratio controls for that amount of excess air. 3. Check and adjust ratio settings regularly.	A32		Check Burner Air to Fuel Ratios www.nrel.gov/ docs/fy08osti/42110.pdf
590	Check heat transfer surfaces: • Examine your flue-side heat transfer surfaces for deposits. • Clean heat transfer surfaces periodically. • Use a soot blower to automatically clean heat transfer surfaces. • Use a soot burn-out practice for radiant tubes or muffles used in high temperature furnaces. • Use continuous agitation or other methods to prevent materials from accumulating on the heat transfer surfaces • Examine your water-side heat transfer surfaces for scale and remove the deposits. • If scale is present, consult with your local water treatment specialist and consider modifying your chemical additives.	A34		Check Heat Transfer Surfaces www1.eere.energy.gov/industry/bestpractices/pdfs/check_heat_transfer_process_htgts4.pdf
591	Maintaining slightly positive furnace pressure	A31		Furnace Pressure Controllers www1.eere.energy.gov/industry/bestpractices/pdfs/furnace_press_control_process_htgts6.pdf
592	Preheating Combustion Air	A24		Install Waste Heat Recovery Systems for Fuel-Fired Furnaces www1.eere.energy.gov/industry/bestpractices/pdfs/install_waste_heat_process_htgts8.pdf
593	Steam Generation and Water Heating	A24		
594	Load Preheating	A24		
595	Load Preheating Using Flue Gases from a Fuel-Fired Heating System	A24		Load Preheating Using Flue Gases from a Fuel-Fired Heating System www1.eere.energy.gov/industry/bestpractices/pdfs/38852.pdf
596	Oxygen-Enriched Combustion	A32		Oxygen-Enriched Combustion www1.eere.energy.gov/industry/bestpractices/pdfs/oxygen_enriched_combustion_process_htgts3.pdf

#	Sustainable Manufacturing practice	Tactic	Sector	Reference
597	Reduce Air Infiltration in Furnaces	A32		Reduce Air Infiltration in Furnaces www1.eere.energy.gov/industry/bestpractices/pdfs/38849.pdf
598	Reduce Radiation Losses from Heating Equipment	A13		Reduce Radiation Losses from Heating Equipment www1.eere.energy.gov/industry/bestpractices/pdfs/38851.pdf
599	Using Waste Heat for External Processes	A24		Using Waste Heat for External Processes www1.eere.energy.gov/industry/bestpractices/pdfs/38853.pdf
600	Use Microwave Processing	A43		Improving Process Heating System Performance www1.eere.energy.gov/industry/bestpractices/pdfs/process_heating_sourcebook2.pdf
601	Preheat combustion air	A24		www1.eere.energy.gov/industry/bestpractices/pdfs/process_heating_sourcebook2.pdf
602	Recover furnace waste heat	A24		
603	Improve maintenance on furnaces to reduce heat losses	A31		
604	Install variable speed drives when appropriate	A43		
605	Optimize air-to-fuel ratios	A32		
606	Optimize cycle length and furnace loading	A32		
607	Preheat process materials and equipment	A24		
608	Waste heat recovery	A24		Indirect-Fired Kiln Conserves Scrap Aluminium and Cuts Costs www1.eere.energy.gov/industry/bestpractices/pdfs/em_proheat_firedkiln.pdf
609	Eliminate Excessive In-Plant Distribution System Voltage Drops	A32		Eliminate Excessive In-Plant Distribution System Voltage Drops www1.eere.energy.gov/industry/bestpractices/pdfs/motor_tip_sheet8.pdf

#	Sustainable Manufacturing practice	Tactic	Sector	Reference
610	Eliminate Voltage Unbalance, Suggested Actions: • Regularly monitor voltages at the motor terminals to verify that voltage unbalance is maintained below 1%. • Check your electrical system single-line diagrams to verify that single-phase loads are uniformly distributed. • Install ground fault indicators as required and perform annual thermographic inspections. Another indicator that voltage unbalance may be a problem is 120 Hz vibration. A finding of 120 Hz vibration should prompt an immediate check of voltage balance.	A32		Eliminate Voltage Unbalance www1.eere.energy.gov/industry/bestpractices/pdfs/eliminate_voltage_unbalanced_motor_systemts7.pdf
611	Replace V-Belts with Cogged or Synchronous Belt Drives	A42		Replace V-Belts with Cogged or Synchronous Belt Drives www1.eere.energy.gov/industry/bestpractices/pdfs/replace_vbelts_motor_systemts5.pdf
612	The new pump handles the same volume as the original pumps during non-peak periods, but runs for longer periods of time. The lower outflow rate reduces friction and shock losses in the piping system, which lowers the required head and energy consumption.	A42	Municipal sewage system	Improving sewage pump system performance www1.eere.energy.gov/industry/bestpractices/case_study_sewage_pump.html
613	Ineffective existing pump speed control was eliminated and the motors were wired for direct on-line start.	A41		
614	Installing a new pump that matched the existing system	A42		Improving the efficiency of a brewery's cooling system www1.eere.energy.gov/industry/bestpractices/case_study_brewery.html
615	Installing a new pump with a variable speed drive	A42		
616	Induced draft fan systems with a VFD	A43	Refuse systems	Improving the performance of a waste-to-energy facility www1.eere.energy.gov/industry/bestpractices/case_study_waste_to_energy.html
617	Retrofitted 15 of the 18 fans with VFDs	A42	Textile	Improving ventilation system energy efficiency in a textile plant www1.eere.energy.gov/industry/bestpractices/case_study_ventilation_textile.html

#	Sustainable Manufacturing practice	Tactic	Sector	Reference
618	Replace the 1magnetic starter and eddy current clutch with a Baldor vector controller(=VFD) and line reactor	A42	Steel pipes and tubes	Improving Efficiency of Tube Drawing Bench www1.eere.energy.gov/industry/bestpractices/pdfs/mc-cs04.pdf
619	Installing variable speed drives (VSDs) on the 2,250-hp primary feed pump and 700-hp product pump	A43	Oil refinery	Motor System Upgrades at Chevron Refinery www1.eere.energy.gov/industry/bestpractices/pdfs/chevron.pdf
620	Replacing the internal elements on the 2,250-hp secondary feed pump and a 400-hp power recovery turbine (PRT)	A42		
621	The modified system uses a smaller pump with an 8" x 10" casing and a 32" diameter impeller with an output that more accurately matches system flow requirements.	A32	Mining	Optimized Pump Systems Save Coal Preparation Plant Money and Energy www1.eere.energy.gov/industry/bestpractices/pdfs/peabody1.pdf
622	The original motor was replaced with a new premium efficiency 200-hp, 1800-rpm motor rated at 96.5 percent efficiency.	A42		
623	The motor slide base should be replaced as a result of extreme corrosion.	A31		
624	Maintenance of the V-belt drive, to prevent corrosion and set the proper tension	A31		
625	Replace 1 out of 3 pumps with a smaller one	A42	Sewage system	Saving Energy at a Sewage Lift Station Through Pump System Modifications www1.eere.energy.gov/industry/bestpractices/case_study_lift_station.html
626	The rest 2 pumps will operate only when the operation load is high	A12		
627	Shut down unnecessary pumps. Re-optimize pumping systems when a plant's water use requirements change. Use pressure switches to control the number of pumps in A2 service when flow rate requirements vary.	A25		Conduct an In-Plant Pumping System Survey www1.eere.energy.gov/industry/bestpractices/pdfs/conduct_in_plant_pumping_systemts1.pdf
628	Restore internal clearances (for pumps).	A31		
629	Replace standard efficiency pump drive motors with NEMA Premium™ motors.	A42		
630	Replace or modify oversized pumps	A42		
631	Meet variable flow rate requirements with an adjustable speed drive or multiple pump arrangement instead of throttling or bypassing excess flow.	A43		
632	Reducing the pumping speed (flow rate)	A32		Control Strategies for Centrifugal Pumps with Variable Flow Rate Requirements www1.eere.energy.gov/industry/bestpractices/pdfs/38949.pdf

#	Sustainable Manufacturing practice	Tactic	Sector	Reference
633	Match Pumps to System Requirements, Identify flow rates that vary 30% or more and systems imbalances greater than 20%.	A34		Match Pumps to System Requirements www1.eere.energy.gov/industry/bestpractices/pdfs/pumping_6.pdf
634	Trim or Replace Impellers on Oversized Pumps, Consider impeller trimming when any of the following apply: • The head provided by an oversized, throttled pump exceeds process requirements. • System bypass valves are open, indicating excess flow rate. • The pump is operating far from its design point. • The operating head and (or) flow rate are greater than process requirements.	A42		Trim or Replace Impellers on Oversized Pumps www1.eere.energy.gov/industry/bestpractices/trim_replace_impellers8.pdf
635	Replace compressed air with fans/blower mixers/nozzles/air conditioning/brushes/blowers/vacuum pumps/electric motors/mechanical pumps for applications with low-pressure end use	A42		Alternative Strategies for Low-Pressure End Uses www1.eere.energy.gov/industry/bestpractices/pdfs/compressed_air11.pdf
636	Apply air storage strategy	A25		Compressed Air Storage Strategies www1.eere.energy.gov/industry/bestpractices/pdfs/compressed_air9.pdf
637	Matching Compressed Air Supply with Demand	A13		Compressed Air System Control Strategies www1.eere.energy.gov/industry/bestpractices/pdfs/compressed_air7.pdf
638	Inspect the entry to the compressor air intake pipe and ensure that it is free of contaminants.	A31		Effect of Intake on Compressor Performance www1.eere.energy.gov/industry/bestpractices/pdfs/compressed_air14.pdf
639	Inspect the compressed air intake filter element to ensure that it is of the appropriate type, that it is properly installed, and that it is clean.	A31		
640	Check the intake filter regularly for excess pressure drop.	A31		
641	Introduce combined heat and power (CHP)	A43	Aerospace	people2.airbus.corp/Transversal_pages/Data/About_Airbus/one_online/HTML/Pages/EN/2009_05_28_5936a6e3-4b89-11de-ba84-0fa16ff26bb7.html
642	Use CHP plants waste emissions as inert gases.	A24		
643	Renovate nitration plant	A31	Synthetic organic dye	Case Study: : Clariant Corporation - Mount Holly
644	Install a 26-stage extraction vessel	A43		

#	Sustainable Manufacturing practice	Tactic	Sector	Reference
645	The vessel extracts from sulfuric acid (by-product) the monochlorobenzene (input)	A15		Plant www.p2pays.org/ref/07/06124.pdf
646	The processed Sulfuric acid is eliminated by hazardous waste and is used as an input for another process (ore beneficiation)	A24		
647	Adjust the PH of Sodium thiosulfate	A15		
648	Sodium thiosulfate (by product) became an input for another process (dechlorination)	A24		
649	Take several aerators totaling 400 horsepower out of service (because the byproduct's process stop earlier)	A41		
650	Install a three-stage air scrubber to remove ammonia emissions from several sulfur dye production areas	A43		
651	Use of ammonium sulfate (byproduct) in a farm as a nutrient.	A24		
652	Start/stop control of cleaning of the printing belt	A13	Textile	Danish experience. Best Available Techniques - BAT - in the clothing and textile industry www2.mst.dk/udgiv/Publications/2002/87-7972-009-0/pdf/87-7972-010-2.pdf
653	Mechanical removal of printing paste	A43		
654	Reuse of the cleanest part of the rinsing water from the cleaning of the squeegees, screens and buckets	A24		
655	Reuse of the rinsing water from the cleaning of the printing belt	A24		
656	Printing paste that is left over after printing can be collected and reused	A24		
657	Change from overflow rinsing to stepwise rinsing	A32		
658	Omit the use of detergents in the rinsing after reactive dyeing of cotton	A21		
659	Omit the use of complexing agents in the rinsing after dyeing	A21		
660	Use only neutralisation after dyeing when using VS reactive dyestuffs	A41		
661	Chemical-free high speed rinsing after reactive dyeing of cotton	A21		
662	Reclamation and reuse of dye bath and first rinse by activated carbon	A43		
663	Reclamation and reuse of rinsing water after dyeing by membrane filtration	A43		
664	Use of enzymatic desizing	A42		
665	Collection and reuse of after treatment chemicals in finishing	A24		
666	Change in spray gun tips	A32	Trucks and bus bodies	Pollurion prevention works for Iowa www.p2pays.org/ref/02/01766.pdf
667	Use a new material can be cleaned from equipment using water	A22		
668	Purchase a new automated hard chrome plating machine to replace the existing hard chrome operation. New line uses a high speed proprietary hard chrome plating process.	A42		caterpillar, Pennsylvania Recovers Hard Chrome www.

#	Sustainable Manufacturing practice	Tactic	Sector	Reference
669	Build a chrome recovery system. The system would allow the conversion of the old line to the new chemistry and close the loop at the source.	A43		p2pays.org/ref/02/01280.pdf
670	The water recovered from the evaporator is to be reused.	A24		
671	Petroleum, naphtha used in vehicle and aircraft parts washing was reduced over eighty percent	A32	Airplanes	The Arizona National Guard Takes Measures to Guard the Environment www.p2pays.org/ref/01/00596.pdf
672	Introduction of jet pressure parts washers (Better Engineering Parts Washers)	A43		
673	Use water and biodegradable soap instead of chemicals	A22		
674	Used jet fuel 'generated by safety fuel checks before aircraft flights generated large amount of waste fuel. Since this fuel cannot be reutilized in aircrafts, the majority of this waste is being blended with diesel fuel and used in ground vehicle operations.	A24		
675	Methyl Ethyl Ketone (MEK) used in painting operations is recycled on-site with distillation units (SolvoSalvager,WestPort Environmental systems)	A15		
676	Methylene Chloride generation of 4,620 pounds per year from painting operations was eliminated and replaced with MEK which is recycled by distillation.	A22		
677	Contaminated Water/fuel is generated during the fueling of aircraft. An activated carbon-filtration system (AquaSorb TM.60 System, Hadley Industries) was installed to filter this mixture. The water is returned to the city sewer, and the activated carbon filters collect the fuel constituents.	A15		
678	Purchased a machine to make decals. Markings on vehicles, aircraft and buildings were previously produced by painting with spray paint cans, but now a machine cuts vinyl with an adhesive backing into desired shapes for decals. The use and Waste of spray paint cans has been reduced significantly.	A13		
679	Petroleum contaminated rags from vehicle and aircraft maintenance generated huge amount of waste. A service was established to' pick-up and launder the contaminated rags and replace with clean rags.	A24		
680	Replace with low or No-HAPs Lacquers/Lacquer Thinners, contain low amounts of or no listed hazardous air pollutants (HAPs).	A22	Wood products & furniture	Product Substitution to Low or No-HAPs Coatings/Coating Solvents www.p2pays.org/ref/01/00289.htm
681	Switch to peroxide, a more environmentally friendly chemical, for bleaching and used chlorine only to clean machines between batches.	A22	Textile	Renfro Corporation www.p2pays.org/ref/07/06112.pdf
682	Install new burners on their boilers	A42		

#	Sustainable Manufacturing practice	Tactic	Sector	Reference
683	Changing sampling procedures and using only one spinning position, the sampling time was cut on the average of 1 hour and reduced all the yarn waste that was produced during the sampling time.	A12	Textile	E.I. duPont de Nemours & Co. - Cape Fear Plant www.p2pays. org/ref/07/06126.pdf
684	Redesign the push-off devices to reduce the number of yarn packages that were bruised by the equipment	A32		
685	After extensive re-engineering efforts, the facility is now able to produce polymer grade TPA, which is reacted directly with ethylene glycol to produce the PET resin. This modification completely eliminates the use of methanol and the production of DMT as an intermediate step in the reaction process, eliminating the methanol emissions and methanol by-product waste associated with that step.	A44		
686	Install a PET recycling facility to reprocess this material. The PET material will be converted to DMT and glycol via methanolysis.	A15		
687	The DMT will be sold to other facilities for fiber production while the glycol is reused in the production process.	A24		
688	All major emissions of VOC generated during the recycling process of DMTwill be diverted to a Dowtherm process heater for waste heat production.	A24		
689	Innovative process modifications in the continuous polymerization units have permitted significant reductions in process temperatures, which, in turn, reduce compound volatilization and atmospheric and waterborne emissions of volatile organic compounds (VOCs).	A32		
690	The fibers facility also modified the exchanger vents and methanol tank vents to reduce methanol emissions.	A32		
691	A cobalt catalyst used in the production of intermediates is now recovered.	A24		
692	Laboratories and parts washers switched to non-halogenated solvents.	A22		
693	Convert the coating system by substituting a two-component urethane (polane) coating for the enamel paint	A15	Electronics	Exide Electronics www.p2pays. org/ref/07/06146.pdf
694	Replace the water wash system with a dry filter booth	A15		
695	The quantity of overspray generated during coating operations was reduced by a switch to high-volume, low-pressure (HVLP) spray guns. The HVLP guns reduce overspray, paint consumption, and the amount of waste material disposed.	A32		
696	Solvents used for equipment cleaning and line flushing are recycled on site with a solvent distillation unit.	A15		

#	Sustainable Manufacturing practice	Tactic	Sector	Reference
697	Replace solvent-based varnishes with water reducible varnishes, thus eliminating another hazardous waste stream	A22		
698	Convert its painting process to a powder coating system	A44	Electronics	ABB Power T&D Company, Inc. www.p2pays.org/ref/07/06145.pdf
699	Over spray goes back through the coating system and is reclaimed and reused	A24		
700	Implemented a filter system in glass shop operation to reduce resin usage.	A43	Fiberglass-reinforced plastics	Miller Control and Manufacturing Co., Inc. www.p2pays.org/ref/07/06150.pdf
701	Substitute solvent-based system with a suitable water-based chemical system (an acrylic latex emulsion)	A42	Textile	Guilford Mills, Inc. www.p2pays.org/ref/07/06110.pdf
702	Change from solvent-based to water based coatings	A42	Tobacco	R. J. Reynolds Company www.p2pays.org/ref/07/06107.pdf
703	Established a waste recycling program with a designated full time coordinator. The coordinator works with six manufacturing facilities and numerous brokers and mills to maximize volume and profit from over thirty different categories of paper, plastic, foil and laminates.	A15		
704	Utilize carbon adsorption and distillation to capture solvent vapors from the printing presses and other packaging manufacturing areas. The collected vapors are then condensed and distilled into a reusable product. Approximately half of the recovered solvent blend is reused in-house for new ink formulations, and the remainder is sold to outside vendors. Most of the solvent is currently sold for use in furniture finishes.	A24		
705	Install a totally enclosed, automated washer system utilizing a non-hazardous solvent for washing printing press parts.	A42		
706	Distillation is used to recover solvent for reuse. Solvent is also recovered from still bottoms by heating the sludge in a large microwave oven.	A43		
707	Ash reuse, co-generation facilities by diverting it for reuse in agricultural products and concrete	A24		
708	Pelletize non-recyclable waste paper for use as fuel in the company's coal fired boilers	A24		
709	Fuel oil was replaced with cleaner natural gas as boiler fuel	A22	Textile	Westpoint Stevens www.p2pays.org/ref/07/06116.pdf
710	Jet dyeing machinery was upgraded to low-liquor-ratio machines with shorter cycles. This modification resulted in reduced chemical, water, and energy usage.	A32		
711	Extensive recycling operations are conducted at the plant for plastic cones, plastic, cardboard cones, wooden pallets, cotton wipes, and scrap cloth.	A15		

#	Sustainable Manufacturing practice	Tactic	Sector	Reference
712	Cardboard spinning tubes were unrecyclable because of the heavy glues used in their manufacture. These tubes were replaced with recyclable PVC cones, which not only last five times longer but can be recycled when they wear out.	A22		
713	By installing a spray vapor condenser, it was able to recapture Glycol, divert it back into the production process, and prevent its release to the atmosphere.	A24	Textile	E.I. DuPont de Nemours & Company DuPont Fibers, Kinston Plant www.p2pays.org/ref/07/06127.pdf
714	During the polymerization process, dimethyl therathalate (DMT) was traditionally reacted with glycol to produce the polyester product and liquid methanol by-product. By substituting therathalic acid (TPA) for the DMT, the plant no longer produces liquid methanol by-product.	A22		
715	The company developed a non-destructive x-ray test method that eliminated the use of solvent for this application, significantly reducing plant-wide solvent consumption.	A44		
716	All parts washing equipment at the plant was converted to utilize non-hazardous (higher flashpoint) solvents. This solvent substitution reduced the quantity of hazardous waste generated.	A22		
717	Titanium dioxide is utilized as a polyester whitening agent. The company installed an automated handling and mixing system that significantly reduces the amount of material lost during the processing of this material.	A42		
718	Preventative maintenance programs significantly reduced the quantity of lube oil waste generated at the facility. These programs included installing longer-life oils in certain equipment.	A13		
719	Freon eliminated as cleaning agent	A22	Pharmaceuticals	Baxter Healthcare Corporation www.p2pays.org/ref/07/06122.pdf
720	Substitution of lab chemicals	A12		
721	The boiler used for steam generation at the facility was converted from oil-fired to wood-fired	A22		
722	Large quantities of waste oil were previously discarded but are now filtered and reused on site.	A15		
723	Substitution of cleaning solvent	A22		
724	Reuse of waste plastic	A24		
725	Convert the degreasing process to a five stage aqueous cleaning line in response to pending air quality regulations and concerns over future liabilities associated with the disposal of methylene chloride still bottoms	A44	Plumbing components and plastic faucets	Moen Incorporated www.p2pays.org/ref/07/06137.pdf
726	A chemical called “Oil Split” was added to the cleaner to separate the oil in the coalescer	A22		

#	Sustainable Manufacturing practice	Tactic	Sector	Reference
727	An evaporation system was installed that successfully evaporated the water from the aqueous wash waste, leaving only a used oil for disposal.	A43		
728	Use electrowinning (plating) to remove copper from the pre-dip tank to prolong the life and improve the control of the Brite Dip plating process	A15		
729	Cyanide brass plating was eliminated and replaced with a metal plating process called physical vapor deposition (PVD). This process is cleaner and reduces the scrap rate on decorator parts by over 10%.	A22		
730	Implement counter-flow rinse tanks and efficient water use practices on the plating lines	A32		
731	Wooden pallets and cardboard are now recycled .	A24		
732	The previous cardboard baler was under-capacity for the volume of cardboard generated and was replaced with a high-density compactor for cardboard.	A42		
733	Apply new heat recovery technology suitable for bakery	A24	Bakery	Cleaner production in bread making - Buttercup Bakeries www.p2pays.org/ref/04/03323.htm
734	Replace the ozone-depleting chemical with a water-based detergent soap degreaser	A22	Textile	Hoechst Celanese Corporation www.p2pays.org/ref/07/06128.pdf
735	Leak detection and repair program was adopted, and selective replacement of valves, pumps, and flanges with leakless equipment was undertaken.	A31		
736	Materials recycled from the facility include office paper, cardboard, mixed wood, pallets, construction debris, scrap metal, used oil, and plastic.	A24		
737	The gaseous emissions are diverted to a single collection point where they are then passed through a distillation unit.	A15		
738	The targeted SARA chemicals are separated and diverted to a waste heat boiler, which generates low-pressure steam for reuse in the plant.	A24		
739	A centrifuge for dewatering the paint booth sludge is being installed. Waste reduction will result from removing water from the sludge requiring disposal.	A43	Construction machinery	Koehring Cranes & Excavators www.p2pays.org/ref/01/00771.pdf
740	The water will be reused in the paint booths	A24		
741	Switch from chemical based paint to water-based	A22	Automotive manufacturing, coatings	Reducing Contaminated Wastewater from Water-Based Paint www.p2pays.org/ref/01/00622.pdf
742	Install a combined ultra-filtration/reverse-osmosis (UF/RO) process to clean up the waste water.	A43		
743	The UF/RO process is recovering 95% of the wastewater	A24		

#	Sustainable Manufacturing practice	Tactic	Sector	Reference
744	Primer coats are applied in powder form. Electrostatic attraction between the powder and the vehicle surface keeps the coating on the surface until the powder is polymerized in a bake oven at 325°F (163°C).	A44	Automotive manufacturing, body repair	Powder Paint System Improves Automobile Coatings, Boosts Environment www.p2pays.org/ref/01/00622.pdf
745	With the powder-paint system the overspray can be captured and recycled. 95% of the paint solids are deposited on the vehicle surface. In comparison, only 43% of the solids are deposited by the paint-spray system.	A24		
746	Discontinue use of all adhesives. Use non-ferric screws to attach insulation to sheet metal parts. Implementation requires the selection of an acceptable fastening method and the purchase of appropriate tools.	A22	Heating, ventilating, and air conditioning equipment	Waste Minimization Assessment for a Manufacturer of Heating, Ventilating, and Air Conditioning Equipment www.p2pays.org/ref/01/00602.pdf
747	Replace all solvent-based adhesives with water-based (nonhazardous) adhesives.	A22		
748	Modify the use of adhesives to maximize the use of water-based (non hazardous) glue. Spot glue 10% of the surface area with the quick-drying solvent-based adhesive and cover the remaining 90% with the slow-drying water-based adhesive.	A13		
749	Install a recirculating air-oil condensing system adjacent to the fin press to reclaim evaporating oil.	A24		
750	Change to high solids paint formulation, utilizing new air assisted, airless electrostatic spray guns, and dedication of individual spray booths for certain colors. The change to high solids formulation included installation of paint heaters to maintain proper viscosity and separate supply and return piping.	A44	Construction machinery	Koehring Cranes & Excavators www.p2pays.org/ref/01/00773.pdf
751	Install an electrostatic spray paint system for priming and painting to reduce overspray losses.	A42	Rebuilt railway cars and components	Waste Minimization Assessment for a Manufacturer of Rebuilt Railway Cars and Components www.p2pays.org/ref/01/00604.pdf
752	Dipping of wood furniture in water based stains to eliminate VOC emissions	A15	Office furnishings manufacturer	Process Change and Raw Materials Substitution in the Office Furnishing Manufacturing Industry www.p2pays.org/ref/01/00157.pdf
753	Conversion of all pigmented wood coatings to water base	A22		
754	Install a closed loop metal treatment system	A24		
755	Recycling of a cardboard, paper, steel and aluminium	A24		
756	Optimize the conservation of wood by use of computerized cutting saws.	A43		
757	Experimented with resin and other powder paint components from various national and international suppliers. The new technology uses about 98 percent of the raw coating material, which is baked onto the metal furniture	A22		
758	Excess powder is collected, cleaned and put back into the spray gun.	A24		

#	Sustainable Manufacturing practice	Tactic	Sector	Reference
759	Install a new rinse system on nickel and chromium plating lines.	A43	Plating services	Hajjar Plating Services www.p2pays.org/ref/01/00842.pdf
760	Filter out insoluble inorganic contaminants from the nickel rinse tanks. This arrangement resulted in a 58 percent reduction in annual water usage.	A15		
761	A water-based equivalent that produces better quality finish with increased wear characteristics has been substituted for white MEK-based paint. Substitute a similar product for a solvent-based yellow paint and clearcoat.	A22		Cooper Hand Tools/Lufkin Manufacturing Facility www.p2pays.org/ref/07/06152.pdf
762	Concentrate and return chromic acid rinse for reuse in the etch tank.	A24		
763	Install a recovery unit on the lines that recovers the nickel and allows reuse of water as rinse make-up on another plating line.	A15		
764	The reclaimed nickel is sent to a recycler. The nickel recovery unit resulted in decreased consumption of rinsewater treatment chemicals and reduced rinsewater use and disposal costs.	A15		
765	The chemical 1,1,1-trichloroethane was phased out and replaced with a citrus-based degreasing agent.	A22	Pulp mill operations	Weyerhaeuser Pulp Facility www.p2pays.org/ref/07/06121.pdf
766	Regular tune-ups and maintenance have minimized the use of ether in start-up of heavy equipment diesel engines.	A31		
767	The polychlorinated biphenyl (PCB) transformers have been removed and replaced with silicon or dry-cast coil transformers.	A42		
768	Install a wet-packed fume scrubber with a recirculation system. This system collected chromium concentrate from two plating tanks.	A43	Electroplating	C & R Hard Chrome and Electroless Nickel Service, Inc. www.p2pays.org/ref/07/06135.pdf
769	Double-walled insulated tanks replaced all heated steel tanks	A42		
770	Single-rinse tanks were switched to a system of counterflow multiple rinse tanks to reduce water consumption	A32		
771	Restrictive flow nozzles on water inlets were added to better control and reduce water consumption	A35		
772	The lifespans of solutions were extended with in-tank filtration systems installed on the alkaline cleaner, hydrochloric acid, and electroless nickel tanks.	A15		
773	With nitric acid stripping solution replaced by hydrogen peroxide, the generation of nitric acid hazardous waste was eliminated	A22		
774	Hydrogen peroxide is sent to a recycler where nickel sulfate is reclaimed for reuse	A24		
775	New “dry” mesh-pad ventilation system reduced air emissions from the process and allowed reuse of any captured fumes	A24		

#	Sustainable Manufacturing practice	Tactic	Sector	Reference
776	Purchase a chrome solution purifier called a porous pot. The porous pot uses electrodialysis concepts in conjunction with ceramic membranes. The continual removal of contaminants significantly lengthened the bath life.	A22		
777	Develop a new process in which a chlorine-free silicon fluid is used as a raw material. With replacement of silicon tetrachloride raw material by the silicon fluid, no hydrochloric acid by-product is generated. This modification eliminated all hydrochloric acid and chlorine gas emissions from the glass manufacturing process.	A42	Telecommunica-tions products	Corning Incorporated www. p2pays.org/ref/07/06132.pdf
778	The silicon dioxide particles not deposited on the fibers during the coating process are collected in a filtration process.	A15		
779	The elimination of hydrochloric acid in the waste stream made it possible for the company to install a filtration media that does not require a protective coating. Thus, the now uncoated silicon dioxide particles can be collected and diverted from the landfill to other manufacturing processes.	A15		
780	Achlorine reduction and germanium recovery system (GRS) was installed, replacing the original wastewater treatment system. In this system, germanium oxide is reacted with magnesium sulfate to form magnesium germanate, and is not released from the facility.	A42	Fiber optic cable manufacturing	Alcatel Telecommunications Cable www.p2pays.org/ ref/07/06133.pdf
781	The germanium-containing wastewater sludge is filtered, dried, bagged, and sold to a manufacturer for re-use.	A15		
782	A new process of integrating the color into the fiber coating without the use of solvent-based inks was introduced. Several modifications to the process equipment and support facilities were conducted to accommodate the new on-line coating system	A42		
783	Chemical Substitution	A22	Textile	Bloomsburg Mills, Inc. www. p2pays.org/ref/07/06108.pdf
784	Heat and Water Reuse	A24		
785	CFCs had been completely phased out and substituted with the halogenated solvent methylene chloride. Methylene chloride worked well as a blowing agent, but is a suspected human carcinogen and a Hazardous Air Pollutant (HAP) under the federal Clean Air Act. Hickory Springs then switched to acetone as a replacement solvent.	A22	Polyurethane foam manufacturing	Hickory Springs Manufacturing Company www.p2pays.org/ ref/07/06131.pdf
786	Yarn manufacturing waste, yarn mill card waste, knitting rags, and finishing rags are collected and baled and then sold to a textile waste recycler. Office paper and scrap metal are also collected for recycling.	A15	Textile	Cleveland Mills Company www.p2pays.org/ref/07/06109. pdf
787	Salt brine replaced sodium sulfate in the dyeing operation.	A22		
788	By upgrading the wastewater treatment system, the facility significantly reduced BOD, COD, and TSS loadings.	A31		

#	Sustainable Manufacturing practice	Tactic	Sector	Reference
789	Formaldehyde air emissions from the manufacturing process were substantially reduced by utilization of low-shade resins that contain a lower percentage of the chemical; quality and performance levels were not compromised by the substitution.	A22		
790	Air emissions from the facility were further improved by replacement of the coal-fired boilers with cleaner natural gas-fired boilers.	A42		
791	Aerosol cans, such as those containing paint or lubricant, were replaced with reusable cans that can be re-pressured with air.	A42	Postal	U.S. Postal Service, Greensboro Bulk Mail Center www.p2pays.org/ref/07/06154.pdf
792	The HVAC system was replaced with a system that uses HCFC's (hydrochlorofluoro carbons), which are more environmentally friendly than traditionally used CFCs	A42		
793	Replace over 90% of their solvent-based paints with water based paints	A22		
794	A new stain eliminated the need for a washcoat and eliminated a sanding step in the production process. Thus the substitution reduced waste generation as well as raw material consumption by eliminating two steps in the production process.	A22	Furniture	Thompson Crown Wood Products www.p2pays.org/ref/07/06118.pdf
795	Purchase a grinder and use this waste material (wood & sawdust) in the company's co-generation facility where it could be burned for energy recovery.	A24		
796	Implement a new glue application system to eliminate glue defects from top and end panels on television cabinets. This modification has enhanced product quality on all cabinets; nearly eliminated rejects due to glue dispensing and application problems; eliminated labor associated with glue cleanup; reduced glue use; and eliminated glue bottle, pan, tip, clean-up rag, and plastic bag waste streams.	A42		
797	Recycling of water-based printing waste	A24		
798	Implement a process change in which end panels are glued at each builder's station instead of along a conveyor. This change has reduced the annual number of glue rejects to zero.	A42		
799	Change paint spray gun	A42		
800	Alter print room process for the application of roll-on finishes for all top and end panels of cabinets. The company successfully diverted 60 percent of the spraying operations from the finish room to a roll-on process in the print room and reduced materials use by 50 percent.	A42		
801	Installation of the powder coater	A42	LPG storage tank manufacturing	Trinity Industries www.p2pays.org/ref/07/06140.pdf
802	Atomization of the coating at low air pressures allows increased transfer efficiency (65-80%), reduced over-spray, and therefore, reduced VOC emissions.	A32	Wood products & furniture manufacturing	Switch to HVLP Spray Gun Equipment for Stains and Sealers www.p2pays.org/ref/01/00286.htm

#	Sustainable Manufacturing practice	Tactic	Sector	Reference
803	Reusing cleaning solvent until it becomes spent	A24	Steel fabrication and coating	Steelfab www.p2pays.org/ ref/07/06138.pdf
804	Reusing spent cleaning solvent for thinning	A24		
805	Switch to water-based cleaner for paint equipment	A22	Wood products & furniture manufacturing	Water-Based Cleaner for Paint Equipment www.p2pays.org/ ref/01/00290.htm
806	Use of waterborne topcoat lacquers	A22	Wood products & furniture manufacturing	Switch to Waterborne Topcoat Lacquers www.p2pays.org/ ref/01/00287.htm
807	Water-based adhesives and solventless hot melt adhesives (100% solids) replaced solvent-based adhesives in the manufacturing processes.	A22	Wood products & furniture manufacturing	Switch to Waterborne Topcoat Lacquers www.p2pays.org/ ref/01/00291.htm
808	The existing mill water system was modified to reduce fresh water consumption and excess thermal loading on the river through water reuse.	A24	Paper manufacture	Champion International Corporation www.p2pays.org/ ref/07/06119.pdf
809	Computer monitoring of water consumption now ensures minimum usage whenever possible.	A34		
810	Further water conservation is achieved through installation of a new 3-cell cooling tower and basin which, by receiving the water and reducing its temperature to 85o F, enables reuse of all excess hot water generated by the pulp mill.	A15		
811	Water conservation is also achieved on two fine-printing and writing paper machines via mesh filtration of process and cooling tower water. The water is then reused on the machines.	A15		
812	New pulp bleaching process utilizes an oxygen delignification step prior to the chlorine bleach step. Oxygen delignification significantly reduces the lignin content of the pulp prior to bleaching, thereby reducing chemical usage and effluent color.	A15		
813	Molecular chlorine as a bleaching chemical has been eliminated and replaced with chlorine dioxide.	A22		
814	The installation of a non-condensable gas collection and incineration system allows the mill to capture and burn odorous sulfide gases formerly emitted to the atmosphere.	A15		
815	Installation of a new condensate stripper	A42		
816	Two sets of evaporators were rebuilt	A31		
817	A third set of evaporators was retired	A41		
818	Cleans use-oil using a filtering system and send it back to the process for reuse	A15	Alloy steel and	The Timken Company www.

#	Sustainable Manufacturing practice	Tactic	Sector	Reference
819	Water-soluble grinding coolant could be reused in the metal turning process, a process that can tolerate a lesser quality coolant.	A15	highly engineered bearings	p2pays.org/ref/07/06144.pdf
820	Reclaimed oil is stored for use as a backup boiler fuel	A15		
821	Redesigned the process to use natural gas	A22		
822	Purchase self-contained water treatment unit. This unit is a hydrogen peroxide treatment system, which removes the VOCs (Volatile Organic Carbons) and hydrocarbons from the grease- and oil-contaminated washwater.	A43	Farm equipment salvage and remanufacture	Mid-East Tractor Parts www.p2pays.org/ref/07/06142.pdf
823	Convert to new flux systems with non-VOC solvent systems and inactive residues.	A44	Printed circuit board assembly	Solectron Technology Incorporated www.p2pays.org/ref/07/06148.pdf
824	Leaky faucet being replaced	A31	Office building	The Office of the Lieutenant Governor www.p2pays.org/ref/41/40952.pdf
825	Old drinking fountain being disconnected	A41		
826	The water bill history is now being kept and analyzed carefully to identify any possible problems with water consumption	A34		
827	Computer turnoff practice	A33		
828	Light turnoff practice in unused areas	A33		
829	Use of desk lamps and natural light instead of ceiling lights	A44		
830	Old office equipment has been replaced with more energy efficient equipment	A42		
831	All but one vent be closed in the basement	A41		
832	“gas pack” systems have been repaired	A31	Office building	North Carolina League of Municipalities www.p2pays.org/ref/41/40951.pdf
833	The heating system goes into energy-saving mode when the building is unoccupied	A13		
834	Thermostat set to a less demanding temperature	A32		
835	Recycled sewage water from the Resort's waste water treatment plant is used to maintain the Resort's landscaping and gardens.	A24	Resort	Cleaner Production - Energy Monitoring System: Ayers Rock Resort www.p2pays.org/ref/04/03309.htm
836	Installation of Preventative Maintenance Computer System	A35		
837	An on-going project at the Resort involves the replacement of 40-50 watt incandescent light bulbs with compact 11 watt fluorescent lamps.	A42		
838	Animal and plant waste is composted on site and used on the zoo grounds. An expansion is planned for the current compost site to handle all animal and plant waste.	A15	Zoo	The North Carolina Zoo www.p2pays.org/ref/07/06167.pdf
839	Employees use bicycles for short trips instead of vehicles, some park rangers use bicycles instead of golf carts,	A42		

#	Sustainable Manufacturing practice	Tactic	Sector	Reference
840	monitor water use and to identify leaks	A34		
841	Thermostats in buildings are on timers to reduce energy use at night	A32		
842	40-watt bulbs are being replaced with 30-watt bulbs.	A42		
843	Return over 90 percent of all wooden cable reels to wire and cable manufacturers for reuse, repair, or recycling	A24	Electric services	Duke Power Corporation www.p2pays.org/ref/07/06157.pdf
844	The facility has replaced disposable oil absorbents and towels with washable towels/wipes.	A22		
845	Replace wood scaffolding with aluminium scaffolding that can be reused indefinitely	A22		
846	Check the quality of air conditioning fans before automatically replacing them	A35		
847	Replace two hazardous cleaners and degreasers with a non-hazardous orange/lemon degreaser	A42		
848	Change parts of washer systems from a hazardous solvent that was changed routinely to a non-hazardous solvent.	A22		
849	Encourage painting crews to mix only the amount of paint necessary for each job	A32		
850	Solvent recovery system was installed to separate waste paint solids from reusable solvent	A15		
851	The paint removal process was changed from sandblasting to a reusable steel shot media.	A15		
852	Wastewater heat exchangers were installed to recover lost BTUs from the waste stream	A24	Textile	Spectrum Dyed Yarns, Inc. www.p2pays.org/ref/07/06114.pdf
853	Economizers were added to the boiler exhaust stacks to recover the heat energy previously emitted to the atmosphere. The heat from the economizers was used to raise the temperature of process water in the plant	A24		
854	Install monitoring and control systems to monitor and control all water system flows, storage tank levels, and water temperatures. The control system also monitors all water in the plant and determines, by temperature, which tank to use for heated water storage.	A34		
855	With the assurance that hot water was always available, the cycle times for a yarn dyeing procedure were then optimized. This also decreased water consumption and allowed all existing equipment to dye more product.	A12		
856	Change cooling tower chemical treatment program and was granted permission. This new process allowed the facility to run higher cycles or concentrations in the tower, thus decreasing county water usage	A42	Electricity generation	Craven County Wood Energy www.p2pays.org/ref/07/06156.pdf
857	Re-lamped its buildings and reduced wattage by 40 percent	A42	Computer software	SAS Institute www.p2pays.org/ref/07/06161.pdf
858	A tracer system, which automatically reduces usage during low peak hours, was installed in many of the buildings to monitor heating and air conditioning	A34		

#	Sustainable Manufacturing practice	Tactic	Sector	Reference
859	Paper cups and other disposables have been replaced with washable items in the break areas, and soda and juice fountains have eliminated cans and bottles	A42		
860	Replace 1,1,1-trichloroethane vapor degreasers with aqueous-based cleaners	A22	Can manufacturing	Crown Cork and Seal Company www.p2pays.org/ref/07/06136.pdf
861	Change the side stripe spray used to a lower volatile spray	A42		
862	Recycle scrap tin plate generated from the cutting process	A15		
863	Source reduction techniques during the manufacturing process to reduce spoilage of the tin plate material	A13		
864	Replace existing generators with reduced capacitors	A42		
865	Install more efficient motors	A42		
866	Switching from a hazardous xylene/toluene to a biodegradable pseudo-cumene solution	A22	Research / non-commercial	Research Triangle www.p2pays.org/ref/07/06168.pdf
867	Unused tritium is re-adsorbed onto a uranium bed	A15		
868	The chemical reduction program resulted in the total elimination of all extremely hazardous chemicals	A22	Textile	Milliken and Co. - Golden Valley Plant www.p2pays.org/ref/07/06111.pdf
869	The company is currently diverting 100% of production-generated solid waste materials from the landfill to recycling markets.	A15		
870	Countercurrent rinses significantly reduce water consumption	A32	Compressed air products manufacturing	Hankison International www.p2pays.org/ref/07/06141.pdf
871	To further extend rinsewater life, an ultrafiltration system was installed on first rinse stage	A43		
872	Recover and reuse chemicals from its electroless plating operation	A15	Additive circuits	Hazardous Waste Reduction www.p2pays.org/ref/01/00761.pdf
873	Sodium hydroxide and formaldehyde are added to the plating bath overflow to recover the copper, which is then dissolved for reuse by a sulfuric acid/hydrogen peroxide solution	A15		
874	Collect scrap aluminium for recycling	A24	Aluminium cans	Waste Minimization Assessment for a Manufacturer of Aluminium Cans www.p2pays.org/ref/01/00603.pdf
875	Reduce water use in the can washing operation to the lowest possible rate	A12		
876	Reduce the concentrations of chemicals used in the can washing operations to the lowest possible values	A22		
877	Use a filter press to reduce the water content of hazardous sludge before shipment off-site for disposal	A15		
878	Oil recycler collect waste oil from the extruder coolant system	A15		
879	Substitute a nonhazardous reagent that contains nitric acid and hydrofluoric acid for the hazardous reagent currently used.	A22		

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880	Replace the chromic acid with phosphoric acid	A22	Communication equipment	Norand Corporation www.p2pays.org/ref/01/00810.pdf
881	A synthetic coolant in their honing process used as an alternatives to the sulphurized oil	A22	Automobile components	Coolant Substitution at Presmet Corporation www.p2pays.org/ref/01/00440.pdf
882	Since the installation of the aqueous jet washer, the facility has been able to eliminate 2 parts washers and 1 carburetor cleaner	A41	Automotive maintenance	North Carolina National Guard Combined Support Maintenance Shop (CSMS) www.p2pays.org/ref/07/06174.pdf
883	Replace the majority of the mineral based solvent cleaners with biodegradable ones.	A22		
884	Replacing oil only when it is contaminated rather than at certain mileage intervals has significantly reduced the frequency of oil changes	A32		
885	Used oil and antifreeze is collected and recycled	A15		
886	The facility sends shop rags for laundering and reuse them	A15		
887	Purchase an industrial centrifuge, which effectively and efficiently separates the fuel product from the absorbent, leaving the pads dry enough for reuse or disposal as a solid waste. This reduced the total hazardous waste at the base by one third.	A24	Federal military installation	Seymour Johnson Air Force Base www.p2pays.org/ref/07/06176.pdf
888	All off-specification fuel reclaimed for use as fuel in the heat plant	A15		
889	EMIS is a centralized computer-based system used to control and track the use of hazardous materials for the entire Air Force Base.	A35		
890	Used oil is collected throughout the base on an as-needed basis. The used oil was donated to Auburn University for use in their heat plant.	A15		
891	A windrow and turning process constructed for the natural treatment of petroleum-contaminated soil combines locally acquired turkey manure with the contaminated soils, encouraging the stimulation of microbes that break down the hydrocarbon products.	A15		
892	Install an innovative metals removal and water recycling system that has virtually eliminated hazardous waste from the largest waste generation process on the facility.	A43	Aircraft servicing and repairing	U.S. Coast Guard Support Center www.p2pays.org/ref/07/06155.pdf
893	Parts washer modifications and solvent replacement reduced solvent-based hazardous waste by 7500 pounds (a 40% reduction).	A22		
894	The still was converted to continuous operation from batch operation to allow the inclusion of more dilute waste streams and to increase the ethanol removal efficiency.	A44	Blood derivatives / plasmas - mfg.	Bayer Corporation - Clayton Facility www.p2pays.org/ref/07/06123.pdf
895	A more aggressive acetone distillation process was initiated and fine-tuned in order to maximize recovery of acetone from the waste stream.	A15		

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896	The addition of an aerating basin before pH treatment and the combination of domestic plant wastewater to process wastewater have reduced the amount of magnesium oxide needed to neutralize the waste stream by approximately 90 percent.	A43		
897	An alum mixing system was installed and a rotary sludge thickener and sludge de-watering device were added.	A43		
898	Reduce the amount of isopropanol discarded as waste by increasing batch life, decreasing overfills, and training employees on solvent use reduction techniques.	A12		
899	Reuses petroleum naphtha cleaning solvents by adding centrifuges to the parts washers to remove particulates and increase batch life of the solvent.	A15		
900	Old antifreeze removed from vehicles is filtered and used for topping off radiators or for use as a counterweight in heavy equipment tires.	A24	Transport	N.C. Department of Transportation www.p2pays.org/ref/07/06170.pdf
901	Many traditional solvents have been replaced with non-hazardous, biodegradable solvents	A22	Federal military installation	Camp Lejeune Marine Corps Base www.p2pays.org /ref/07/06172.pdf
902	Solvent distillation units used during painting operations to recycle spent solvents	A24		
903	Many items previously disposed in municipal waste landfills, i.e., yard and food waste, mixed paper, and biomass ash, are now utilized in the Base pilot composting project.	A15		
904	This compost is used as a soil amendment on Base.	A24		
905	Install a 35 gallon capacity batch-distillation unit to recover 90% of the solvent for reuse.	A15	Tobacco products	Liggett & Myers Tobacco Company www.p2pays.org /ref/11/10153.pdf
906	Replaced 1,1,1-trichloroethane vapor degreasing system with two aqueous-based cleaning systems	A42	Household equipment	Household Toaster and Toaster Oven Manufacture www.p2pays.org/ref/07/06147.pdf
907	The new aqueous cleaner is recycled through a ceramic crossflow ultrafiltration unit, which removes submicron contaminants and oils.	A15		
908	A sludge dryer and a filter press were installed to reduce the quantity of sludge landfilled.	A15		
909	Process modifications permit a percentage of recovered scrap material to be reground, blended with virgin resin, and reused in the injection molding process.	A14		
910	Other reuse and recycling projects adopted at the facility include the purchase of a baler to handle cardboard waste. Aluminium, steel, and bronze metal scrap from the pressing operations are collected and recycled, and metal and plastic drums used to ship materials to the facility are returned to the vendors for reuse or recycling.	A15		

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911	A pretreatment facility was installed and enabled much of the wastewater to be treated and re-circulated back into the production process.	A15	Recycled cardboard	Jackson Paper Company www.p2pays.org/ref/07/06120.pdf
912	By installing a holding tank, effluent water could be collected and reused in the showers in place of fresh water.	A24		
913	Mill wastewater diverted for use as boiler scrubber makeup water in place of fresh water	A24		
914	Waste material could be collected and used as fuel for wood fired boilers to generate steam	A24		
915	A small hopper was modified and dust is collected and combined with the product run residuals. These materials are now stored and recycled back into the same product the next time it is manufactured.	A15	Animal feed manufacturer and distributor	Furst-McNess Company www.p2pays.org/ref/07/06103.pdf
916	Reduce hazardous chemicals use	A32	Pharmaceutical	Wyeth-Ayerst Laboratories www.p2pays.org/ref/07/06129.pdf
917	Renovate the wastewater pre-treatment system	A31		
918	Incorporate scrap shingles into the hot-mix asphalt pavement produced in both their plants. The scrap material is hauled from a local shingle manufacturer.	A24	Asphalt plant / asphalt paving - contractors	C.C. Mangum, Inc./us www.p2pays.org/ref/07/06100.pdf
919	Process scrap from off-spec material was reduced by the installation of a process control computer, which allows operators to constantly monitor the product material and permits immediate shutdown of the process if the material is off-spec.	A35	Roofing materials	CertainTeed Corporation www.p2pays.org/ref/07/06130.pdf
920	Scrap sold to paving companies to be mixed in asphalt for parking lots and driveways.	A15		
921	Fiberglass mat excess material is baled and shipped to a company for reuse in insulation, and the cardboard cores are returned to the supplier for reuse.	A15		
922	A wastewater monitoring program was implemented	A34	Glass packaging	Cleaner Production Demonstration Project at ACI Glass Packaging www.p2pays.org/ref/04/03334/
923	Improve oil separation, involving installation of a new hydrocyclone-style separator.	A42		
924	Install a biosol collection and recycling system	A15		
925	A system has been installed to collect the dust from key areas and return it to the conveyor, to be reused in the batch.	A15		
926	Selling a brewing by-product as liming material to local farmers	A24	Brewery	Miller Brewing www.p2pays.org/ref/07/06105.pdf
927	The plant replaced wooden pallets with returnable plastic pallets	A22	Textile	Springs Industries, Inc. www.p2pays.org/ref/07/06115.pdf
928	Hazardous cleaning solvent replaced with a non-regulated cleaner with double the life-span in all parts washers.	A22		
929	Reuse the size mixture.	A24		

#	Sustainable Manufacturing practice	Tactic	Sector	Reference
930	Both aluminium and plastic are recycled in the production areas	A24	Company sign	Sign Art www.p2pays.org /ref/07/06153.pdf
931	Water used in processing snack foods is high in proteins, carbohydrates, and other nutrients is applied as a fertilizer to growing turf and sod	A24	Snack foods and nursery products	Eagle snacks www.p2pays.org /ref/07/06102.pdf
932	A centrifuge recovery system collects starch from potato washing operations for subsequent sale to an animal feed formulator.	A24		
933	Additional plates were added to the wastewater treatment sludge filter press and procedural changes were made to reduce treatment time and remove more water from the sludge. This reduces the amount of sludge requiring disposal.	A15	Transportation bushings and bearings	Glacier Vandervell, Inc. www. p2pays.org/ref/01/00645.pdf
934	Water is micro-filtered to remove solids (lead and others) and be recycled.	A15		
935	A backwash system was installed to maintain filtration viability.	A43		
936	Nickel recovery from plating waters	A15		
937	New infra-red ovens provide fast, energy-efficient drying of glued sections.	A42	Wood products	Kinnear door www.p2pays.org/ ref/03/02101.pdf
938	Recycle and reuse of water	A24		
939	Reduce ethanol emissions and wastewater BOD discharges. By distilling ethanol from dilute waste streams.	A15	Brewery	The Stroh Brewery Company www.p2pays.org/ref/07/06106. pdf
940	Ethanol produced can be used as motor fuel additive or industrial raw material.	A24		
941	Install a counter-current system on rinse tanks and an ion exchange system to remove contaminants from rinse water. Contaminated overflowing rinse water is pumped through pre-filter unit, caution column to remove metals, and anion column to further purify water.	A15	Electroplating	Amplate, Inc. www.p2pays.org/ ref/07/06134.pdf
942	Recycle and reuse of water	A24		
943	The company has been able to increase bath life of the alkaline cleaning solutions by proper selection of chemicals, in-tank filtration to remove insoluble contaminants, and treatment of other contaminants.	A13		
944	A coagulant is used periodically in the acid pickle tanks to remove metal contamination without the usual pH adjustment. As a result, an acid pickle bath has not required dumping and replacement in over two years.	A13		
945	Electroless nickel is suitable and sometimes superior replacement to hard chrome in some applications. The company is experimenting with a new nickel-tungsten-boron coating that shows promise as a replacement for hard chrome for many applications.	A22		
946	Re-circulating rinse baths	A24	Metal finishing	Tin Originals Inc. www. p2pays.org/ref/07/06139.pdf
947	Re-circulating rinse increases the concentration of zinc in the rinse.	A15		

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948	Flow controls were installed on two tap-water rinses in the mid-sized system and on three tap-water sprays in the large system.	A35	Electrocoating	Wastewater and chemical use at L&J of New England, www. p2pays.org/ref/01/00162.pdf
949	Two filters were installed on the initial cleaning tanks for the midsized and large systems.	A43		
950	First tank of cleanup water for each process batch for reuse as cutwater in the next batch.	A24	Specialty dyes and color additives	Ciba Specialty Chemicals Corp. USA www.p2pays.org/ ref/41/40953.pdf
951	Using more efficient hose nozzles providing better pressure and spread, while using less water for the same floor area.	A42		
952	Use plastic sleeves instead of masking paint to prevent chrome plating of piston ring.	A42	Combustion engine piston rings	Pollution Prevention Assessment for a Manufacturer of Combustion Engine Piston Rings www.p2pays.org/ ref/03/02819.pdf
953	Replace 1,1,1-trichloroethane vapor degreasing with a high pressure hot water spray system for removal of machining residues prior to plating.	A22		
954	Purchase a solvent distillation unit to regenerate spent solvents	A15		
955	Utilize all of the three existing cold water rinse tanks to completely remove chromic acid from piston rings, thus elimination the need for manual spray rinsing.	A22		
956	Filtration of dye bath wastewater	A15	Textile	Sara Lee Knit Products www. p2pays.org/ref/07/06113.pdf
957	Recycle and reuse of water	A24		
958	Install a nanofilter to separate the water from the oily waste stream.	A15	Motor	Outboard Marine Corp. www. p2pays.org/ref/07/06143.pdf
959	Reclamation tank to filter and recirculate cleaning solution to reduce chemical consumption	A15	Screen printing	T.S.Designs www.p2pays.org/ ref/07/06117.pdf
960	With the installation of a holding tank, all water used in the degreasing process is recycled for use in the reclamation cleaning process.	A24		
961	Eliminate the use of solvents by substituting a water-based adhesive	A22		
962	Install an ion-exchange silver recovery unit, the company now receives some of the profits from reclamation of the silver metal.	A15		
963	The water from the washing process is reused in the production process.	A24	Dairy products	Coastal Dairy Products, Inc. www.p2pays.org/ref/07/06101. pdf
964	The use of concentrated cleaner and the washwater reuse are expected to significantly decrease both cleaning chemical use and water consumption.	A24		
965	Used ammonia compressor and freezer oil from the refrigeration system are collected for cleaning and reuse by an oil recycling firm.	A15		
966	Food waste are given to a local hog farmer	A15		
967	The scrap metal generated from equipment replacement and maintenance, which includes stainless steel, iron and copper, is sold to a local scrap metal dealer for recycling.	A15		