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The emergence of sustainable manufacturing practices

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Sustainable manufacturing appears to be a rapidly developing field and it would be expected that there is a growing body of knowledge in this area. Initial examination of the literature shows evidence of sustainable work in the areas of product design, supply chain, production technology and waste avoidance activities. Manufacturers publish metrics showing significant improvements in environmental performance at high level but information on how these improvements are achieved is sparse. Examining peer reviewed publications focused on production operations there are few cases reporting details and there has been little prior analysis of published sustainable manufacturing activity. Moreover, the mismatch between academic and practitioner language leads to challenges in interpretation. This paper captures and analyses the types of sustainable manufacturing activities through literature review. In turn this can help manufacturers to access examples of good practice and help academics identify areas for future research.

Keywords: sustainable manufacturing; literature review; best practice; case studies

Introduction

Population growth combined with developing countries' demand for the life-style of industrialised countries creates increasing pressures on our planet. The need for sustainable development constitutes the greatest challenge in human history. Early environmental activities were associated with corporate citizenship and corporate social responsibility (Matten and Crane 2005). Nowadays, legal and financial incentives are making the adoption of environmentally-sound business practices a question of sustaining business economically over time.

Manufacturing clearly has a major contribution to make towards a more sustainable society. The motivations for manufacturers to become more proactive in improving their environmental performance are increasingly linked to cost reduction: material and energy inputs as well as waste disposal costs have dramatically increased over the last decade as finite resources diminish. Evidence of environmental degradation has driven tougher legislation and resulting punitive costs for non-compliance. Public interest in environmental and social performance of companies also steers the market towards cleaner and more ethical products and practices.

Early work in sustainable manufacturing was carried out under the label of Environmentally Conscious Manufacturing (ECM). It included considerations for source reduction, dismantling, design for manufacturing and assembly as well as cradle-to-reincarnation concepts (Owen 1993). Later development of ECM done by Sarkis identified three dimensions to ECM strategies (product, process and technology) and the strategies themselves constitute the famous ‘Rs’: reduction, remanufacturing, recycling and reuse (Sarkis 1995; Sarkis and Rasheed 1995).

Current improvements in manufacturing are focused on lean manufacturing (Lewis 2000, Yang 2011), product design (Waage 2007, Tan *et al.* 2010), and the ‘Rs’ strategies (Fleischer *et al.* 2007). Whilst measures of performance improvements are showing brand name companies are moving towards sustainable manufacture, detail on implementation is difficult to find. In cases where details are available the focus tends to be on the specific technology rather than from a broader industrial engineering perspective. Thus there is a need to review and document the current state of activities and develop a knowledge library in order to drive academic research and disseminate best practices among manufacturers.

In order for academics and practitioners to understand the extent of current practice and disseminate it, there is a need to understand what work has been carried out to date and what motivated it. Current sustainable manufacturing practices are not well mapped and therefore the justification and mechanism for improvements and their impacts are unclear. A better understanding in this area could support better adoption of sustainable manufacturing principles. This paper therefore presents an analysis of current practice adoption to assess where work has been done and what has motivated it.

Sustainable frameworks and models

Sustainable development is defined as meeting the needs of the present without compromising the ability of future generations to meet their own needs (WCED, 1987). It is a simple matter to manipulate this definition for sustainable manufacturing. It can be defined as a new paradigm for developing socially and environmentally-sound techniques to transform materials into economically-valuable goods.

Sustainable development is well-defined and widely recognised as a key concept for a safer future. The 3Ps (People, Planet, Profit) or 3BL (Triple Bottom Line) (Elkington 1997) underline that sustainable development is not only about addressing environmental issues, but it tackles three encompassing dimensions: economic, social and environmental. Practically, many child-concepts have been developed to support sustainable development at various levels of activity, such as sustainable manufacturing and industrial ecology (Frosch and Gallopoulos 1989), ecological footprint (Wackernagel and Rees 1996) 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.* 2009) and whole supply chain simultaneous with the design of products and production systems (Srivastava 2007, Haapala *et al.* 2008). They cover 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, 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).

To achieve sustainable manufacturing, there are rules defined by various authors. Major changes are needed to move towards more sustainable industrial practices (Lovins *et al.* 1999, Allwood 2005, Abdul Rashid *et al.* 2008):

1) Use less by dramatically increasing the productivity of natural resources (material and energy);
2) Shift to biologically inspired production models such as reduction of unwanted outputs and conversion of outputs to inputs: recycling and all its variants, cleaner production, industrial symbiosis;
3) Move to solution-based business models including changed structures of ownership and production: product service systems, supply chain structure.
4) Reinvest in natural capital through substitution of input materials: non-toxic for toxic, renewable for non-renewable;

To summarise, sustainability requires improved resource use-productivity (Seliger *et al.* 1997, Seliger *et al.* 2008) in order to reduce natural resource inputs as well as consequent waste and pollutant outputs.

Industrial ecology models emphasise the move from a linear to a closed-loop circulation of resources. These models take a 'black box' view of the industrial system. The focus is on inputs and outputs of the system, resource-use productivity and eco-efficiency. This systems perspective allows the shift from local (sometimes suboptimal) solutions to more global and effective solutions in order to achieve a shift from linear 'type I' to more closed loop 'type II' or 'type III' system as illustrated in Figure 1. It also helps to avoid overlooking some resource flows and unforeseen release to the ecosphere by using mass balance to make sure it complies with the first law of thermodynamics. It emphasises industrial systems' interactions with the environment in an integrated way.

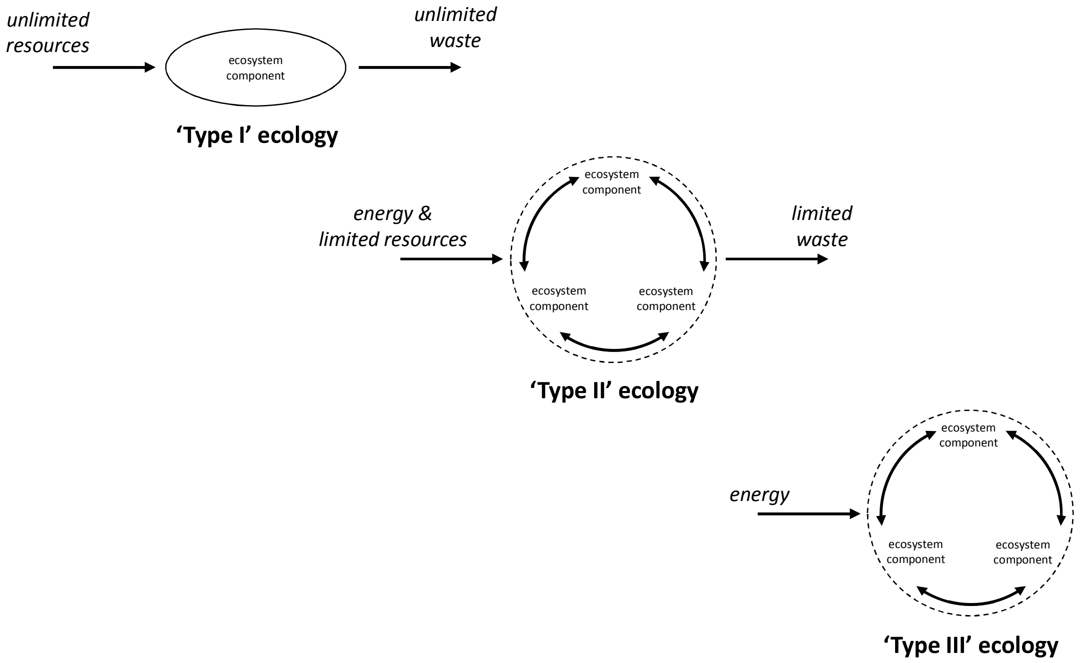

Figure 1: Systems view in industrial ecology (Graedel, 1994).

Such ecosystem components could be established as sub-systems within a single enterprise or across multiple enterprises where the waste outputs of a process can be used by another. For example, Yuan and Shi (2009) describe both internal reuse and reuse by other enterprises of smelter waste.

Over the decades, advanced computing techniques (Garetti and Taisch 1999) have developed tremendously together with computing capacity. Modelling and optimisation techniques have proven to be a reliable tool to support manufacturing improvements. Modelling and simulation techniques integrating material, energy and waste flows (Ball *et al.* 2009b) can help to understand interactions between processes. They can improve resource-use productivity by identifying losses from the system which can be used elsewhere as a valuable input. Such closed loop material flow and reduction in virgin material consumption is illustrated in Figure 2. It shows the value added to material from the resource extraction (from the ecosphere) as it flows throughout the industrial system (through the technosphere) until it reaches its end-of-life. This conceptual model views the manufacturing system as part of a bigger system and clearly shows how the 'Rs' strategies can retain value by closing the loop within the technosphere. One example of reuse and recycling is given by Wiendahl *et al* (1999) for a disassembly factory.

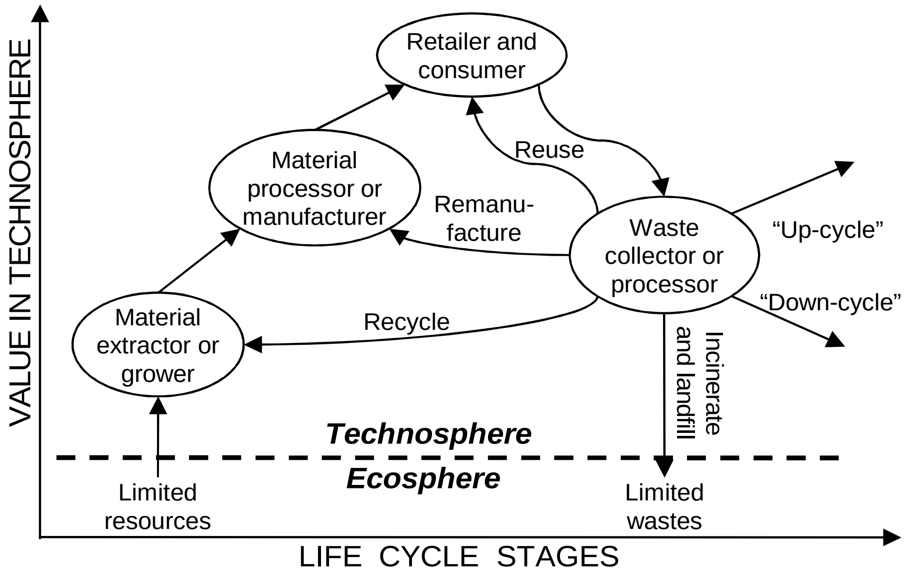

Figure 2: Convert waste into resource input to keep value (Ball *et al.* 2009a).

Figure 2 shows the life cycle stages of material and hence the immediate association of the material that forms the final product. Viewing material in its widest form as a resource it is extended to include consumables, water, air, etc. Whilst these may not reach the consumer they are extracted, used, potentially re-used and eventually lost as waste. Energy can be treated in a similar way in that the dominant energy forms are a result of extraction, transformation, possible reuse and eventual loss. Significant energy conversion and loss is incurred within each life cycle stage, such as the material processor or manufacturer stage.

By considering materials and energy together, say at the manufacturer stage, the production system, its buildings and the supporting infrastructure can be considered together. Treating these as ecosystem components within a larger system offers potential for greater reuse and recycling. Such a wider view would include any surrounding industry or community. The perspective of this research broadens the view of sustainable manufacturing activities and has the potential to uncover a wider range of cases reported in the literature and a wider range of practices employed.

So what evidence is there that companies have moved from 'Type I' ecology to more closed loop practices? Are these practices 'pure lean' practices or are they pursuing a wider agenda? If there is significant evidence of sustainable manufacturing practices, are there frameworks, models and methodologies emerging to guide others beyond reporting on specific technological changes? This paper examines research that aims to establish what practices have been reported in the area of sustainable manufacturing, specifically from an industrial engineering perspective.

Research design

3.1 Methodology

Research is a strategic way of building knowledge to innovate products, processes, production systems, industrial organisations and business models in order to achieve sustainability goals in manufacturing. Science-based disciplines, especially industrial engineering, contribute to turn research results into innovative solutions for companies to meet society needs while respecting the limits of the planet in an efficient way.

The area of sustainable manufacturing is a rapidly developing field, but yet there are few quality reports on current levels of sustainable manufacturing activities in companies. Thus, this research aims to fill this gap by providing a collection of practices obtained from cases reported. By documenting and analysing these cases, it will allow manufacturers to view examples of good practice and help academics to identify areas for future research.

A review of the state-of-the art in sustainable manufacturing was conducted to understand the necessity and emergence of this relatively new field, and the ensuing main dimensions and concepts. Particular attention was paid to available enablers of sustainable manufacturing.

Case studies of sustainable practice in industry were collected from the literature and reputable web sites. The data collected was mapped against defined criteria and a lifecycle model to establish current practice. Finally an analysis was carried out to identify changes in sustainable practices in industry.

3.2 Data collection method

Recalling the different terminology used in the literature for the sustainable manufacturing field, a set of keywords listed in Table 1 was used to gather information from established databases of peer reviewed sources and selected web sources.

Table 1: Keywords used for case studies collection.

Discipline	Sector	Area of application	Filter cases	Type of activity
sustainable	manufactur*	Energy	case	reduc*
green	production	waste	practice	recycl*
eco-friendly	process	material	implement*	reuse
environment*	industry	water	applicat*	recover*
clean		air		conserv*
lean		carbon		
low		emission		
zero				

The keywords were collected from initial examination of peer reviewed sources, trade journals and websites such as the environmental pages of brand name manufacturers. It should be noted that there is a challenge to link the keywords commonly used in *general* academic publications with the terminology used in the *detailed* cases available that can be classed as relating to sustainable manufacture.

The selection of keywords in Table 1 describes the subject area. The keywords from each of the five columns are included in searches. The first column contains keywords describing the discipline, the second column identifies the sector, the third column contains application keywords, the fourth filters publications reporting application and the fifth contains the focus of the application. Different combinations where used to obtain the raw list of cases before exclusion criteria were applied. For the search string, the OR operator was used to group keywords within a column and the AND operator used to group between columns.

Sources included were books from journal publishers, commercial academic search engines, university catalogues, trade journals, academic conferences and respected websites. The initial searches were based on relatively recent publications (2000 to date). References from publications found on the initial searches were also included resulting in older publications being included.

From the sources obtained exclusion criteria were applied. Conceptual publications and those which could not be related to practice in companies were removed. Secondly, those publications that had only anecdotal evidence of practice were ignored (i.e. the evidence presented must be objective). Finally, those publications with insufficient detail to make objective judgements of the type of activity and its impact were removed. These exclusion criteria were applied in parallel reducing the focus from the original many thousands of sources. The final list of cases was then analysed in detail and used for the analysis presented here.

Sustainable manufacturing activity

Due to the complexity of cases, relevant categorisation was used to compare and rationally assess the developments in sustainable manufacturing practices.

Data were first classified within five descriptive categories: sector, company name, sustainable practice type, savings resulting from the practice and sustainable practice description. An example is shown in Table 2. In order to perform a consistent analysis, cases were then categorised according to area of improvement and benefits drawn from the implementation of sustainable practices. The categorisation considered two sets of criteria (primary and secondary) and the three pillars of sustainable development (people, profit, planet). The primary criteria were to objectively classify the data, the secondary criteria assessed the data against the product lifecycle and environmental impact.

Table 2: Example of information extraction from the case studies.

Number	Area	Company	Activity/Type	Savings	Description
Case 1	Steel industry	Weirton Steel	Compressed Air System Improvements Increase Production at a Tin Mill	Reduced compressor shutdowns, production downtime and product rejects Better efficiency of the system lower energy and maintenance costs	Installation of new compressors Leak reparation Initial cost $246,000
Case 2	Automotive glass	Visteon Corp.	Millwater Pumping System Optimization Improves	3.2 GWh per year $280,000 per year Higher efficiency and lower demand for process cooling water Use of Variable Speed Drives to match the system output to the plant's demand more efficiently Reduction of water treatment chemical purchase/use	Renovation of the pumping system Initial cost: $350,000
Case 3	Metal forging	Modern Forge	Compressed Air System Optimisation Project improves production at a Metal Forging Plant	Lower energy use and lower maintenance costs Improved product quality	Improvement of the compressed air system Initial cost: $105,000
Case 4	Automotive aluminium	AAP Saint Mary's	Aluminium Recycling in after-market aluminium automotive wheels production	Energy savings 15.6 Btu Aluminium waste reduced from 8% to 1.5% Cuttings oils now recycled cost savings: 1.60$ per wheel ($1.9M/yr)	DOE's grant of $300,000 In-house chip reclamation Advanced furnace with better recovery and fewer pollutants than the off-site melting process

4.1 Primary criteria

Primary criteria listed in Table 3 were used to classify information drawn from the cases to keep the maximum level of objectivity, namely:

- Generic criteria that capture the cases dispersion in terms of location, date and sector;
- Criteria related to the publication to appreciate the pertinence and objectivity of the cases;
- Analytical criteria that enable discussion on the sustainable practices themselves: what motivates the implementation, what is the focus of the environmental impact, what are the benefits and how the savings are described and measured (practice improvement focus).

Table 3: Detailed primary criteria types.

Type	Criteria
Generic	Geography Year of the practice implementation Industrial sector
Publication	Type of publication Year of publication Focus of the publication
Analytical	Motivation for implementation Metrics of the savings Benefits expressed Practice improvement focus

4.2 Secondary criteria

Breaking down the last primary criterion above of ‘Practice improvement focus’, secondary criteria were defined for the interpretation and analysis of industrial practices as shown in Table 4. Two types of secondary criteria were used successively to study the improvement practices in more detail:

1) ‘Environmental impact’ criteria which describe the environmental impact addressed by the production process change:
    - Energy use reduction;
    - Air emissions reduction/elimination (heat, solvent, carbon, ...);
    - Water use reduction;
    - Wastewater emissions reduction/elimination;
    - Material use reduction;
    - Material waste reduction/elimination (solid waste, hazardous waste).
2) Under each ‘environmental impact’ criterion, six sub-criteria were defined as **CARDFS**. The first four relate to the product lifecycle model and the last two relate to the environment around the production system:

- **C**omponent stage in the lifecycle;
- **A**ssembling stage in the lifecycle;
- **R**ecycling stage in the lifecycle;
- **D**own-cycling stage in the lifecycle;
- **F**acilities modification;
- **S**ervices to business or to the community.

Table 4: Examples of analysis using secondary criteria.

	PRACTICE IMPROVEMENT FOCUS																																			
Case #	Energy use						Air emissions						Water use						Wastewater						Material use						Material wastes					
	c	A	r	d	f	s	c	a	r	d	f	s	c	a	r	d	f	s	c	A	r	d	f	s	c	a	r	d	f	s	c	a	r	d	f	s
1					■																															
2					■												■						■													
3					■																															
4					■																												■			
5					■																												■			
6		■																				■												■		

Relating back to the literature review and Figure 2, **C** and **A** relate to the Materials processor or manufacturer stage and **R** and **D** relate to the ‘Rs’ strategies. Finally, **F** and **S** relate to the wider view of manufacturing of not simply production technology but the ecosystem components that support or can exist in the same system in the technosphere.

4.3 Benefits expressed categorisation against SD three pillars

To highlight the motivations for implementing sustainable practices, an analysis of the benefits expressed was carried out, an example of which is shown in Table 5. These benefits were distributed in areas that recall the three pillars of sustainable development (SD): people, profit and planet. The criteria used for classifying the benefit was as follows: that the major benefit was the highest or only claimed benefit; the medium benefit related to a gain that was shown to be significant but not highest; the lower benefit related to lesser and/or peripheral gain. A shaded differentiation outlines the contribution of the benefits expressed to each area.

Table 5: Practical application of the analysis to case studies by interpreting the benefits expressed in the cases.

Case no.	People	Profit	Planet
1		█	
2		█	
3		█	
4		█	▓
5	░	█	▓
6		█	▓
7	░	█	▓

█ Major benefit
▓ Medium benefit
░ Lower benefit

4.4 Mapping

The combination of different classifications against the primary and secondary criteria provides a wide view of practices and options available for improvement. This mapping allows the identification of current patterns in sustainable manufacturing.

Table 6 gives an example of mapping with a view of the complete table including the descriptive categories, primary and secondary criteria, and the area(s) of the expressed benefits.

Table 6: Example of industrial cases mapping.

	Practice improvement focus																																				Benefits expressed		
Case #	Energy use						Air emissions						Water use						Wastewater						Material use						Material waste						People	Profit	Planet
	c	a	r	d	f	s	c	a	r	d	f	s	c	a	r	d	f	s	c	a	r	d	f	s	c	a	r	d	f	s	c	a	r	d	f	S			
1					■																																	█	
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8						■																														■		█	▓
9					■						■																								■			█	▓
10	■				■						■			■			■			■																		█	▓
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16		■												■												■													█
17	■																								■													█	▓
18	■																									■												█	▓
19		■			■												■						■															░	█
20		■																								■			■			■	■		■			░	█

Findings

This section discusses the findings of the case analysis summarised in Appendix 1. References for these cases are located in Appendix 2.

5.1 Literature challenges for the analysis

In general, the literature lacks sufficiently detailed companies cases on sustainable manufacturing to conduct a mapping as described above. Many of the cases found were from books dedicated to sustainable manufacturing and from environmental organisation publications and membership organisations websites. However, there are a growing number of conferences and projects reported in academia on sustainable manufacturing that outline the practical applications of sustainable concepts.

In total 83 cases were selected based on the search strategy described earlier. The number obtained and subsequently considered was lower than expected given the breadth of the search terms used, the years covered and the level of anecdotal and reported activity. The requirement for the detail of changes made and the benefits obtained was highly influential in the actual number of cases selected for analysis. It is therefore observed that the level of detailed reporting of actual work carried out in manufacturing companies and the resulting benefits is low. Appendix 1 summarises the cases against the environmental categories of energy, air emissions, water and wastes.

The origin and benefits expressed in the cases examined are shown in Table 7 whilst Table 8 shows the sector and the improvement focus. A broad spread in terms of geography, industrial sector and practice focus is evident. The benefits expressed are notably skewed towards economics and environment.

Table 7: Geographical origin and expressed benefits of the cases.

	People		**Profit**		**Planet**		
	All	**Major**	**All**	**Major**	**All**	**Major**	**Total**
Global	1	0	4	1	5	5	**6**
North America	4	0	20	16	20	9	**25**
South America	1	0	6	3	5	4	**7**
Europe	1	0	14	4	18	14	**18**
Africa	4	0	13	2	11	11	**13**
Asia	2	1	5	0	12	11	**12**
Oceania	0	0	1	0	2	2	**2**
Total	**13**	**1**	**63**	**26**	**73**	**56**	**83**

Table 8: Sector and focus of the improvement work.

Sector and focus	**Energy use**	**Air emissions**	**Water use**	**Waste water**	**Material use**	**Material waste**	**Number of cases**
Agriculture	3	1	2	3	2	2	**6**
Automotive	7	4	7	4	9	4	**13**
Aerospace	0	0	0	1	0	0	**1**
Cement	1	2	0	0	2	1	**2**
Chemical	3	4	1	1	2	4	**5**
Petroleum	1	0	0	1	1	2	**3**
Electrical goods	0	1	1	0	0	1	**2**
Electronic devices and computer	1	1	1	1	0	1	**2**
Food and beverage	2	0	4	4	0	2	**5**
Oil and soap	0	0	1	1	2	0	**2**
Paper and printing	3	0	2	1	1	2	**3**
Wood Furniture	1	1	0	1	2	1	**2**
Textile	4	0	3	4	2	2	**6**
Metals	11	6	1	1	2	6	**14**
Casting	1	0	0	1	2	1	**3**
Machining	2	0	1	1	1	0	**2**
Non-specific	6	3	1	1	3	6	**12**
Totals	**46**	**23**	**25**	**26**	**31**	**35**	**83**

5.2 Improvement measurement

Manufacturers publish significant improvements in metrics at high level (such as increased product quality, productivity, energy and water savings), and associated economic savings, through the use of company annual reports and website summaries. Understandably, it is typical that shallow or no details are given on how these improvements are achieved.

Most of the metrics expressed are operational performance indicators (OPI), which means that in most of the cases, progress towards sustainability has been measured against processes, facilities and equipment performance (Starkey 1998). Three different types of OPI have been identified:

- Conventional operational performance metrics: productivity, efficiency, product quality, maintenance rate, failure rate, etc.;
- ‘Operations’ impact’ environmental performance metrics: energy and water use, solid waste and wastewater rate, pollutant emissions, etc.;
- ‘Prevention’ environmental performance metrics: potential for disassembly/reuse/recycling.

Companies do measure their management performance and environmental condition but these metrics have been noticed mostly for the cases related to environmental organisation projects or when the environmental condition is necessary for the business continuity (e.g. community impact rate). Environmental organisation projects often focus on social benefits so management indicators such as job creation/preservation are often expressed.

Table 9 illustrates the results of the research in terms of metrics for sustainable practices impact found. Most of the metrics can be classed as lagging, with few leading metrics to indicate likely performance improvements in the future. This could suggest that the infrastructure for sustainable manufacturing activities in companies has yet to mature.

Table 9: Types of indicator and metrics expressed in the case studies.

Management performance indicators (MPI)	Operational performance indicators (OPI)	Environmental Condition Indicators (ECI)
Profits/savings	Productivity/efficiency	Community impact rate
Job preservation rate	Energy use	Noise level
Job creation	Water use	
Employee satisfaction rate	Maintenance rate	
Health & Safety results	Product quality	
Innovation potential	Solid waste rate	
Space requirements	Reuse rate	
	Wastewater rate	
	Carbon/gas/ air emissions rate	
	Hazardous products use	
	Failure rate	
	Potential for disassembly/ reuse/recycling	
	Wastewater treatment rate	
	Waste recovery rate	
	Heat losses rate	
	Hazardous sludge volume	

5.3 Maturity of the field

Interestingly, the overall literature searched lacked descriptions of failures or practices implementation shortfalls. This is in contrast to mature disciplines such as lean, project management and enterprise resource planning (ERP) where papers often describe implementation failures and quote project failure rates in double digit percentages. Only industrial research will enable understanding of the issues that companies can face when implementing sustainable practices. The area is not mature enough to get both positive and negative feedback on sustainable practices implementation.

5.4 Motivation for sustainable practices implementation

One important tendency observed is the economic motivation for reducing costs and improving productivity. Many cases are also motivated by the environment and society (government incentives, sector/customer pressure, environmental legislation, new standards) resulting in companies integrating more and more sustainability in their corporate strategy and ethics. This recalls again the three interrelated dimensions of sustainability (people, planet, profit) and shows that companies are mostly moving towards sustainability by compliance to societal changes and requirements.

5.5 Implementation strategies

Implementation strategies of sustainable practices expressed in the cases match Allwood (2005) and Seliger's (2004) approaches and strategies for sustainable manufacturing.

Table 10 summarises the results of the research in terms of common practices employed by the companies towards sustainability that was earlier illustrated in Table 2. Results have been obtained by scoring using the frequency of practices for each lifecycle stage in a particular environmental area. The columns relate to changes to the CARDFS secondary criteria described earlier. Table 10 is drawn from the summary of practices contained in cases found shown in Appendix 1. The table does not present only where practices will appear; it presents where practices are more commonly reported.

Table 10: Common implementation strategies highlighted from the research.

	Modification of sub-**C**omponents	Modification of **A**ssembly process	**R**ecycling	**D**own-cycling	Modification of production **F**acilities	**S**ervices to businesses or to community
Improving energy use	X	X			X	X
Improving water use		X	X		X	
Improving material use		X	X	X	X	
Reducing air emissions					X	
Reducing wastewater		X	X		X	
Reducing material waste		X	X	X	X	X

5.6 Benefits expressed

The ranking of the sustainable practices benefits expressed in the cases shows environmental benefits are considered as most important benefits followed closely by economic ones (see Table 7). Interestingly, social aspects are never expressed as major benefits. When looking at the frequency of expressed benefits in the cases, economic and environmental benefits are prevailing. It is noted from these cases that financial outcomes from sustainable practices are predominant over corporate citizenship motivations.

Discussion

Despite a thorough data collection method combining a broad range of keywords and consistent databases, the literature does not contain significant numbers and complete illustrations of sustainable practices in industry. Information is particularly deficient regarding quantification of benefit, 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 concerns, environmental activities are now part of the many corporate strategies. The large range of terms and notions used in the literature can negatively impact the discussion and knowledge shared among researchers and practitioners (Abdul Rashid *et al.* 2008). Seliger *et al.* (2008) emphasises the challenge of communication in sustainable manufacturing. This work supports this view with a diverse range of terms being used in describing the cases. As a result, there is an extensive use of terms like ‘eco’ or ‘green’ but there are currently no standards concerning the terminology.

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 recall the existing terminology of sustainable manufacture used by academics. This difference can be explained by the fact that sustainable manufacture is a new field spreading in academia and the practitioner community but not yet adopted as a *framework* in the business community.

The different cases showed that current practices for sustainability are aligned with Allwood’s and Seliger’s approaches and strategies for sustainable manufacturing even if the language is different from what used in the sustainable manufacturing field literature. As a result, a categorisation of the current sustainable practices against the existing frameworks could help guide companies new to the field.

From the analysis of the benefits expressed from sustainable practices implementation, it appears that environmental impact reduction and economic benefits predominate over social aspects. But details on how these improvements are achieved remains to be further explored.

The key messages therefore to extract for this work for practice are:

- There appears to be significant activity in the area of sustainable manufacturing but this is not well documented by industry or academia. Hence, practices need to be gained first hand from direct company contact as well as use of literature.
- Care needs to be exercised not to use narrow language when examining sustainable manufacturing work as there is diversity in how the work is labelled.
- When considering the benefits for operations improvement, work in this area as expected cites environmental impact as a primary motivation and this is invariably supported by economic benefit. Social motivations are less dominant.
- There is a wealth of metrics for assessing the impact of sustainable manufacturing activities. It should be noted that most are lagging indicators with few examples of leading indicators to guide future work.

Conclusion

The introduction of sustainable manufacturing practices is clearly taking place within industry. The translation of sustainable manufacturing principles into an operational activity is a blind spot on which this research sheds light. Current sustainable improvements reported are mainly focused on design, supply chain, technology and waste avoidance activities and there has been little prior analysis of published sustainable manufacturing activity.

This paper is an attempt to help manufacturers envisage examples of practice and to help academics identify areas for future research by reviewing current literature on sustainable manufacturing activities.

The first observation is the need for manufacturers and researchers to document, analyse and publish more cases on the practice and benefits of sustainable manufacturing. The use of common terminology between academics and practitioners will assist in the accessibility of these cases.

The data collection was performed using a set of keywords covering the subject over a wide range of industrial sectors. The size of the sample was not representative enough to show sector specific trends in the industry practices. The source of information mostly provided the outcomes of sustainable manufacturing practice implementation rather than the means, with a certain bias due to the focus of the organisation or the publication (energy/waste/water, managerial/technological, etc.). This is illustrated through the annual reports and corporate websites for companies showing the metrics but not necessarily the changes made and is supported by analysis of the literature. The study revealed the lack of details on how companies achieve the improvements reported. The metrics used are operation performance indicators (OPI) which shows that it is possible to move towards sustainable manufacturing. It was noted that the indicators tended to be lagging with few leading indicators in evidence. Additionally, there were no reported cases of failure in the implementation of sustainable manufacturing practices which could help others in understanding the problems faced with implementation.

Word count to here: 5400 inc abstract and tables.

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Appendix 1. Categorisation of the practices obtained from the cases against environmental categories and potential strategies and tools to address (source reference in appendix 2).

Environmental category	Area of change	Change practices	Change focuses highlighted from the practices	Key strategies and tools available
Energy	**C:** component	. Material substitution: less weight, better efficiency . New machining method . Virtual development	. Manufacturing strategy (product and process design) . Losses . Process efficiency . Energy supply (source and control) . Process control . Equipment (efficiency and control) . Housekeeping	. Industrial ecology: energy audit . Lean & green: value stream mapping, Pareto, 5 why's . Integrated view: modelling tools . Technology assessment . Eco-balances . Environmental indicators: Operational Performance Indicators
	A: assembly	. Renewable source of energy . Energy capture in low pressure steam . Elimination of bottlenecks . Cleaning using an oil skimmer . Adjust energy supply for varying load requirements . Control of heat exchange and evaporation . Process efficiency increased . Process optimisation . Energy baseline . Better housekeeping		
	R: recycling	. Reuse of steam condensate . Energy reusing		
	D: downcycling	. Recovery of steam condensate		
	F: facilities	. Equipment upgrade for better efficiency . Leakage reparation . Computerized equipment . High efficiency lamps, ballasts and motors . Variable speed drives . Installation of bare steam pipes . Temperature controller . Improved boiler efficiency by reducing air-fuel ratio . Steam pump and piping network . Steam insulation . Briquetting technology . Metering		
	S: services	. Trading of waste to other business or local community as input for their energy supply		

Environmental category	**Area of change**	**Change practices**	**Change focuses highlighted from the practices**	**Key strategies and tools available**
Air emissions	**C:** component	. Virtual Development	. High temperature equipment . Dust released . Solvent use . Heat released . Mounting process . Cooling process . Manufacturing strategy	. Integrated view: simulation tools (tracking) . Technology assessment . Environmental auditing . Eco-balances . Environmental indicators: Operational Performance Indicators . Industrial ecology: emissions inventory . Lean & Green: Value stream mapping
	A: assembly	. Replacement of CO_2 per compressed air for cooling parts . Virtual development		
	R: recycling	. Reuse of furnace gas . Recycling of bypass dust		
	D: downcycling	none		
	F: facilities	. Solvent recovery system . Filter . Increase unit efficiency . Improve furnace isolation . Upgrade furnace . Upgrade oven . Replacement of modular type by rotary type of electronic component in mounting machines		
	S: services	. Piping of heat generated by buildings to local community facilities		

Environmental category	**Area of change**	**Change practices**	**Change focuses highlighted from the practices**	**Key strategies and tools available**
Water use and wastewater	**C:** component	. Virtual Development	. Manufacturing strategy . Process efficiency . Hazardous material use . Water management . Wastewater management . Equipment efficiency and control . Housekeeping . Losses	. Industrial ecology: water audit . Integrated view: Modelling and simulation tools (tracking) . Lean & green: value stream mapping . Technology assessment . Pollution prevention techniques . Eco-balances . Environmental indicators: Operational Performance Indicators
	A: assembly	. Hazardous substances substitution or elimination . Process optimisation . Steam condensate collection . Process change: segregation of the cooling water, vacuum water and process water . Water use efficiency increased		
	R: recycling	. Mechanical vapour recompression . Water recirculation . Processing water reuse . Reuse of steam condensate . Pre-cleaning of parts with dirty solvents for limiting the water use in a second cleaning process . Recirculation of water for cooling and heating		
	D: downcycling	. Water cleaning using an oil skimmer . Anaerobic treatment of organic nutrients in wastewater to produce biogas . Filtration		
	F: facilities	. Equipment upgrade . Equipment efficiency increased . Leakage reparation . Equipment modification . Current counter flow . Automatic shut-off valves . Centrifuge to reduce the water content of the sludge . Visual controls and displays throughout the plant		
	S: services	none		

Environmental category	**Area of change**	**Change practices**	**Change focuses highlighted from the practices**	**Key strategies and tools available**
Material use and waste	**C:** component	. Consideration of disassembly, reuse and recycling issues during product design . Smaller material input before processing . Virtual development	. Manufacturing strategy (product and process design) . Housekeeping . Waste management . Process efficiency . Equipment efficiency . Hazardous material use	. Industrial ecology: emissions inventory . Waste audit . Lean & green: value stream mapping . Integrated view: Modelling tools & simulation tools (tracking) . Material flow analysis . Life cycle assessment/analysis . Eco-balances . Environmental indicators: Operational Performance Indicators
	A: assembly	. Material use efficiency increased . Process optimisation . Material substitution when hazardous . Better housekeeping		
	R: recycling	. Cutting oils recycling . Scrap and slag reuse and recycling . Solid waste recycling . Sorting of the wastes		
	D: downcycling	. Waste recovery system . Treatment of the wastes		
	F: facilities	. Preventive maintenance of the equipment for limiting failures . Closed loop material supply . Waste collection system . Equipment upgrades . Visual controls and displays for increasing employees' awareness . On-site recycling		
	S: services	. Trading of waste as input to other business or local community (eco-industrial park)		

Appendix 2. Reference list for case analysis.

The following list of references provides the sources for the cases listed in Appendix 1.

Sector	Specific subject	Year[1]	Source
Aerospace	Identification of substitute Materials	1998	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.
Agriculture	Process optimisation	2007	El-Haggar, S. (2007), *Sustainable Industrial Design and Waste Management: Cradle-to-cradle for Sustainable Development*, 1st ed, Elsevier Academic Press, California, USA.
Agriculture	Reduction of milk losses	2007	El-Haggar, S. (2007), *Sustainable Industrial Design and Waste Management: Cradle-to-cradle for Sustainable Development*, 1st ed, Elsevier Academic Press, California, USA.
Agriculture	Cleaner production in the sugarcane industry	2007	El-Haggar, S. (2007), *Sustainable Industrial Design and Waste Management: Cradle-to-cradle for Sustainable Development*, 1st ed, Elsevier Academic Press, California, USA.
Agriculture	Sugar cane	2006	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.
Agriculture	Leather	2003	Stoop, M.L.M., 2003. Water management of production systems optimised by environmentally oriented integral chain management: Case study of leather manufacturing in developing countries. *Technovation*, 23(3), 265-278.
Agriculture	Beet sugar	2006	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.
Automotive	Millwater Pumping System Optimization Improves	2003	Energy Efficiency & Renewable Energy, U.S. Department of Energy: http://www.osti.gov/glass/Best%20Practices%20Documents/Assessment%20Case%20Studies/Millwater%20pumping%20system.pdf
Automotive	Aluminium Recycling in after-market aluminium automotive wheels production	1998	California Energy Commission: http://www.energy.ca.gov/process/pubs/toolbook.pdf [last access 13/12/2010]
Automotive	Industrial Heat-Treating (carburizing)	1998	Energy Efficiency & Renewable Energy, U.S. Department of Energy: http://www.osti.gov/bridge/purl.cover.jsp?purl=/755966-XRptCL/native/ [last access 13/12/2010]
Automotive	Applying Design for Environment (DfE) methodology to Rapid Manufacturing (RM)	2006	N Hopkinson, Y Gao, D J McAfee, 2006. Design for environment analyses applied to rapid manufacturing. *Proc. IMechE Part D: Journal of Automobile Engineering*, 220 (10), 1363-1372
Automotive	Cleaner production in metal parts machining	2007	Seliger, G. (2007), *Sustainability in Manufacturing: Recovery of Resources in Product and Material Cycles*, 1st ed, Springer Berlin Heidelberg, Berlin, Germany

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[1] Year of the project or year the paper was written

	processes		
Automotive	Cleaner production in a vehicle transmission manufacturing process	2007	Seliger, G. (2007), *Sustainability in Manufacturing: Recovery of Resources in Product and Material Cycles*, 1st ed, Springer Berlin Heidelberg, Berlin, Germany
Automotive	Cleaner production for the assembly of a camshaft drive	2007	Seliger, G. (2007), *Sustainability in Manufacturing: Recovery of Resources in Product and Material Cycles*, 1st ed, Springer Berlin Heidelberg, Berlin, Germany
Automotive	Caterpillar, Making sustainable progress possible	2008	International Conference on Sustainable Manufacturing 23-24 Sept. 2008 (OECD, Rochester, NY, USA): http://www.oecd.org/dataoecd/47/4/41503487.pdf
Automotive	General Motors, Sustainable manufacturing for Future Automotive Propulsion Technologies	2008	International Conference on Sustainable Manufacturing 23-24 Sept. 2008 (OECD, Rochester, NY, USA): http://www.oecd.org/dataoecd/46/47/41503423.pdf
Automotive	Environmental Eco-Efficient practices	2007	Business in the community: http://www.bitc.org.uk/resources/case_studies/afe1259_ford.html
Automotive	Achieving zero waste to landfill	2004	Business in the community: http://www.bitc.org.uk/resources/case_studies/afe256envtoyota.html
Automotive	Sustainable Lean Manufacturing	2004	Network for Business Innovation and Sustainability: http://nbis.org/nbisresources/operations_product_service_management/lean_mfg_casestudy_genie.pdf
Automotive	Forklift manufacturing	2009	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.
Casting	Infrared Drying	1998	California Energy Commission: http://www.energy.ca.gov/process/pubs/toolbook.pdf [last access 13/12/2010]
Casting	Cleaner production on a casting manufacturing process	2007	Seliger, G. (2007), *Sustainability in Manufacturing: Recovery of Resources in Product and Material Cycles*, 1st ed, Springer Berlin Heidelberg, Berlin, Germany
Casting	Pollution prevention in a zinc die casting company	2002	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.
Cement	Cleaner production in the cement industry	2007	El-Haggar, S. (2007), *Sustainable Industrial Design and Waste Management: Cradle-to-cradle for Sustainable Development*, 1st ed, Elsevier Academic Press, California, USA.
Cement	Envionmental impact of cement production	2009	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.
Chemicals	Re-engineered Fertilizer Production	1998	American Council for an Energy-efficient Economy: http://www.aceee.org/P2/p2cases.htm [last access 31/05/2009]

Chemicals	Saving Energy in the Chemical Industry	1998	American Council for an Energy-Efficient Economy: http://www.aceee.org/P2/p2cases.htm [last access 31/05/2009]
Chemicals	Fine chemical	2009	Wernet, G., Conradt, S., Isenring, H.P., Jiménez-González, C. and Hungerbühler, K., 2010. Life cycle assessment of fine chemical production: a case study of pharmaceutical synthesis. *International Journal of Life Cycle Assessment*, 1-10.
Chemicals	Soda ash (Chemicals)	2006	Kasikowski, T., Buczkowski, R., Cichosz, M. and Lemanowska, E., 2007. Combined distiller waste utilisation and combustion gases desulphurisation method. The case study of soda-ash industry. *Resources, Conservation and Recycling*, 51(3), 665-690.
Chemicals	Chemical factory toxic release	2008	Yu, Q., Zhang, Y., Wang, X., Ma, W.C. and Chen, L.M., 2009. Safety distance assessment of industrial toxic releases based on frequency and consequence: A case study in Shanghai, China. *Journal of hazardous materials*, 168(2-3), 955-961.
Electrical goods	Cleaner production in household appliance manufacturing processes	2007	Seliger, G. (2007), *Sustainability in Manufacturing: Recovery of Resources in Product and Material Cycles*, 1st ed, Springer Berlin Heidelberg, Berlin, Germany
Electrical goods	Panasonic, Reduction of carbon emissions by increasing the productivity	2008	International Conference on Sustainable Manufacturing 23-24 Sept. 2008 (OECD, Rochester, NY, USA): http://www.oecd.org/dataoecd/45/0/41508285.pdf
Electronic devices and computer	IBM cools data centre with swimming pool	2008	Turton, S. (2008), "IBM cools data centre with swimming pool", PC Pro: computing in the real world, [Online], , accessed on: 15 june 2009 available at: http://www.pcpro.co.uk/news/184539/ibm-cools-data-centre-with-swimming-pool.html
Electronic devices and computer	Water Use and Wastewater Reduction	1998	Energy Efficiency & Renewable Energy, U.S. Department of Energy: http://www.osti.gov/bridge/purl.cover.jsp?purl=/663334-Dr42De/webviewable/ [last access 13/12/2010]
Food and beverage	Bioenergy recovery in a brewery production plant	1998	American Council for an Energy-Efficient Economy: http://www.aceee.org/P2/p2cases.htm [last access 31/05/2009] New York State Department of Environmental Conservation, NYS Governor's Awards for Pollution Prevention: http://www.dec.ny.gov/public/22539.html [last access 13/12/2010]
Food and beverage	Conservation of water and energy	2007	El-Haggar, S. (2007), *Sustainable Industrial Design and Waste Management: Cradle-to-cradle for Sustainable Development*, 1st ed, Elsevier Academic Press, California, USA.
Food and beverage	Water Recycling & Treatment System	1998	California Energy Commission: http://www.energy.ca.gov/process/pubs/toolbook.pdf [last access 13/12/2010]
Food and beverage	Distillery water use	2003	Saha, N.K., Balakrishnan, M. and Batra, V.S., 2005. Improving industrial water use: Case study for an Indian distillery. *Resources, Conservation and Recycling*, 43(2), 163-174.
Food and beverage	Food and cleaner production	2003	Kupusovic, T., Midzic, S., Silajdzic, I. and Bjelavac, J., 2006. Cleaner production measures in small-scale slaughterhouse industry - case study in Bosnia and Herzegovina. *Journal of Cleaner Production*, 15(4), 378-383.
Machining	Aqueous Cleaning System	1998	North Carolina Division of Pollution Prevention and Environmental Assistance: http://www.p2pays.org/ref/01/0056537.pdf [last access 13/12/2010]
Machining	Ultrasonically Assisted Cutting of Intractable Materials	NK	Babitsky V, Mitrofanov A and Silberschmidt V, 2004. Ultrasonically assisted turning of aviation materials: simulations and experimental study . *Ultrasonics*, 42 (1-9): 81-86.
Metals	Compressed Air System Improvements	2000	Compressed Air Challenge, Library, Case Studies: http://www.compressedairchallenge.org/library/casestudies/weirtons.pdf

	Increase Production at a Tin Mill		
Metals	Compressed Air System Optimisation Project improves production at a Metal Forging Plant	2000	Compressed Air Challenge, Library, Case Studies: http://www.compressedairchallenge.org/library/casestudies/moddr.pdf
Metals	Innovation in the Die Steel Forging Industry	1998	California Energy Commission: http://www.energy.ca.gov/process/pubs/toolbook.pdf [last access 13/12/2010]
Metals	Waste re-use: Systems and Technology for Advanced Recycling (STAR)	1998	North Carolina Division of Pollution Prevention and Environmental Assistance: http://www.p2pays.org/ref/02/01094.pdf [last access 13/12/2010]
Metals	Fabricated Metal Products Manufacturer	1998	American Council for an Energy-Efficient Economy: http://www.aceee.org/P2/p2cases.htm [last access 31/05/2009]
Metals	New Dispersion Strengthened Low Cost Ductile Cast Iron for Light Weight Components (DILIGHT)	NK	Loughborough University: http://wolftest.lboro.ac.uk/research/manufacturing-technology/SMART/sustainable-projects-students.htm
Metals	Wire rods factory	2007	El-Haggar, S. (2007), *Sustainable Industrial Design and Waste Management: Cradle-to-cradle for Sustainable Development*, 1st ed, Elsevier Academic Press, California, USA.
Metals	Cleaner production in Aluminium Foundries	2007	El-Haggar, S. (2007), *Sustainable Industrial Design and Waste Management: Cradle-to-cradle for Sustainable Development*, 1st ed, Elsevier Academic Press, California, USA.
Metals	Cleaner production in the Iron and steel industry	2007	El-Haggar, S. (2007), *Sustainable Industrial Design and Waste Management: Cradle-to-cradle for Sustainable Development*, 1st ed, Elsevier Academic Press, California, USA.
Metals	Steel technologial change and emissions	2004	Lutz, C., Meyer, B., Nathani, C. and Schleich, J., 2005. Endogenous technological change and emissions: The case of the German steel industry. *Energy Policy*, 33(9), 1143-1154.
Metals	Foundry cleaner technology	2007	Pal, P., Sethi, G., Nath, A. and Swami, S., 2008. Towards cleaner technologies in small and micro enterprises: a process-based case study of foundry industry in India. *Journal of Cleaner Production*, 16(12), 1264-1274.
Metals	Steel eco-efficiency	2009	Van Caneghem, J., Block, C., Cramm, P., Mortier, R. and Vandecasteele, C., 2010. Improving eco-efficiency in the steel industry: The ArcelorMittal Gent case. *Journal of Cleaner Production*, 18(8), 807-814.
Metals	Toxicity in aluminium production	2006	Koehler, D.A. and Spengler, J.D., 2007. The toxic release inventory: Fact or fiction? A case study of the primary aluminium industry. *Journal of environmental management*, 85(2), 296-307.
Metals	Reverse Logistics in	2005	Logožar, K., Radonjič, G. and Bastič, M., 2006. Incorporation of reverse logistics model into in-plant recycling process: A case of

	aluminium		aluminium industry. *Resources, Conservation and Recycling*, 49(1), 49-67.
Non-specific	Mexican manufacturing	1965-1999 (published 2005)	Aguayo, F. and Gallagher, K.P., 2005. Economic reform, energy, and development: The case of Mexican manufacturing. *Energy Policy*, 33(7), 829-837.
Non-specific	Dry cleaning	2006	Altham, W., 2007. Benchmarking to trigger cleaner production in small businesses: dry-cleaning case study. *Journal of Cleaner Production*, 15(8-9), 798-813.
Non-specific	Industrial area synergy	2008	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.
Non-specific	Indian manufacturing	2009	Mukherjee, K., 2010. Measuring energy efficiency in the context of an emerging economy: The case of indian manufacturing. *European Journal of Operational Research*, 201(3), 933-941.
Non-specific	Eco-industrial park energy cogeneration	2008	Strafelt, F. and Yan, J., 2008. Case study of energy systems with gas turbine cogeneration technology for an eco-industrial park. *International Journal of Energy Research*, 32(12), 1128-1135.
Non-specific	Industrial area waste management	2009	Tarantini, M., Loprieno, A.D., Cucchi, E. and Frenquellucci, F., 2009. Life Cycle Assessment of waste management systems in Italian industrial areas: Case study of 1st Macrolotto of Prato. *Energy*, 34(5), 613-622.
Non-specific	Water resource protection	2001	Chour, V., 2001. Water resources protection today: End-of-pipe technology and cleaner production. Case study of the Czech Odra River watershed.
Non-specific	Thermal power generation	2006	Murty, M.N., Kumar, S. and Dhavala, K.K., 2007. Measuring environmental efficiency of industry: A case study of thermal power generation in India. *Environmental and Resource Economics*, 38(1), 31-50.
Non-specific	Industrial ecosystem	2007	Okkonen, L., 2008. Applying industrial ecosystem indicators: Case of Pielinen Karelia, Finland. *Clean Technologies and Environmental Policy*, 10(4), 327-339.
Non-specific	Policies for waste management	2009	Costa, I., Massard, G. and Agarwal, A., 2010. Waste management policies for industrial symbiosis development: case studies in European countries. *Journal of Cleaner Production*, 18(8), 815-822.
Non-specific	Industrial park waste management	2006	Geng, Y., Zhu, Q. and Haight, M., 2007. Planning for integrated solid waste management at the industrial Park level: A case of Tianjin, China. *Waste Management*, 27(1), 141-150.
Non-specific	Regional bio-waste management	2005	Lang, D.J., Binder, C.R., Stauffacher, M., Ziegler, C., Schleiss, K. and Scholz, R.W., 2006. Material and money flows as a means for industry analysis of recycling schemes. A case study of regional bio-waste management. *Resources, Conservation and Recycling*, 49(2), 159-190.
Oil and soap	Oil and fats recovery from industrial wastewater effluent	2007	El-Haggar, S. (2007), *Sustainable Industrial Design and Waste Management: Cradle-to-cradle for Sustainable Development*, 1st ed, Elsevier Academic Press, California, USA.
Oil and soap	Waste minimisation	2007	El-Haggar, S. (2007), *Sustainable Industrial Design and Waste Management: Cradle-to-cradle for Sustainable Development*, 1st ed, Elsevier Academic Press, California, USA.
Paper and printing	Mechanical Vapor Recompression Heat Pump Recaptures Steam	1998	Energy Efficiency & Renewable Energy, U.S. Department of Energy, *Energy Matters*, pp.2, September/October 1999: http://www1.eere.energy.gov/industry/bestpractices/energymatters/pdfs/em_volume7.pdf [last access 13/12/2010]
Paper and printing	Experience on Cleaner Production Audit	2001	International Conference on Cleaner Production (Sept 2001, Beijing, China): http://www.chinacp.org.cn/eng/cpconfer/iccp01/iccp13.html

Paper and printing	Energy savings in pulp and paper industry	2007	Laaksometsä, C., Axelsson, E., Berntsson, T. and Lundström, A., 2009. Energy savings combined with lignin extraction for production increase: Case study at a eucalyptus mill in Portugal. *Clean Technologies and Environmental Policy*, 11(1), 77-82.
Petroleum	Cleaner production for drill cuttings in the petroleum sector	2007	El-Haggar, S. (2007), *Sustainable Industrial Design and Waste Management: Cradle-to-cradle for Sustainable Development*, 1st ed, Elsevier Academic Press, California, USA.
Petroleum	Refining and petrochemicals	1997	Soji Adeyinko, 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.
Petroleum	plastics and packaging and the furniture industries	2007	Russell, S.N. and Allwood, J.M., 2008. Environmental evaluation of localising production as a strategy for sustainable development: a case study of two consumer goods in Jamaica. *Journal of Cleaner Production*, 16(13), 1327-1338.
Textile	Variable Speed Drives	1998	Energy Efficiency & Renewable Energy, U.S. Department of Energy: http://www1.eere.energy.gov/industry/bestpractices/case_study_ventilation_textile.html [last access 13/12/2010]
Textile	Replacement of the sulfur black dyeing in textile companies	2007	El-Haggar, S. (2007), *Sustainable Industrial Design and Waste Management: Cradle-to-cradle for Sustainable Development*, 1st ed, Elsevier Academic Press, California, USA.
Textile	Combining preparatory processes in textile companies	2007	El-Haggar, S. (2007), *Sustainable Industrial Design and Waste Management: Cradle-to-cradle for Sustainable Development*, 1st ed, Elsevier Academic Press, California, USA.
Textile	Conservation of water and energy	2007	El-Haggar, S. (2007), *Sustainable Industrial Design and Waste Management: Cradle-to-cradle for Sustainable Development*, 1st ed, Elsevier Academic Press, California, USA.
Textile	Automated Dye Bath Reuse	1998	DOE Scientific and Technical Information: http://www.osti.gov/bridge/servlets/purl/751074-fDSCHD/webviewable/751074.pdf [last access 13/12/2010]
Textile	Water conservation in textile industry	2006	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.
Wood Furniture	Innovation in the Printing Industry	1998	California Energy Commission: http://www.energy.ca.gov/process/pubs/toolbook.pdf [last access 13/12/2010]
Wood Furniture	Waste and pollution minimisation	2007	El-Haggar, S. (2007), *Sustainable Industrial Design and Waste Management: Cradle-to-cradle for Sustainable Development*, 1st ed, Elsevier Academic Press, California, USA.