

# Industrial Ecology at factory level – A conceptual model

M. Despeisse, P. D. Ball, S. Evans, and A. Levers

*Department of Manufacturing, School of Applied Science, Cranfield University, Cranfield, UK*

## Abstract

Growing environmental concerns caused by natural resource depletion and pollution need to be addressed. One approach to these problems is Sustainable Development, a key concept for our society to meet present as well as future needs worldwide. Manufacturing clearly has a major role to play in the move towards a more sustainable society. However it appears that basic principles of environmental sustainability are not systematically applied, with practice tending to focus on local improvements. The aim of the work presented in this paper is to adopt a more holistic view of the factory unit to enable opportunities for wider improvement. This research analyses environmental principles and industrial practice to develop a conceptual manufacturing ecosystem model as a foundation to improve environmental performance. The model developed focuses on material, energy and waste flows to better understand the interactions between manufacturing operations, supporting facilities and surrounding buildings. The research was conducted in three steps: (1) existing concepts and models for industrial sustainability were reviewed and environmental practices in manufacturing were collected and analysed; (2) gaps in knowledge and practice were identified; (3) the outcome is a manufacturing ecosystem model based on industrial ecology (IE). This conceptual model has novelty in detailing IE application at factory level and integrating all resource flows. The work is a base on which to build quantitative modelling tools to seek integrated solutions for lower resource input, higher resource productivity, fewer wastes and emissions, and lower operating cost within the boundary of a factory unit.

**Keywords** Industrial Ecology; Sustainable manufacturing; Resource flow modelling; Sustainability.

## 1 Introduction

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 (customers, shareholders, employees, governments, etc.) are asking for more environmentally responsible business practice (Hart, 1995). More recently, the move towards more sustainable business practices has become a question of sustaining economically one's business on the long-term: in the current context of increasingly stringent environmental policies, improving the company's environmental performance is linked to long-term cost reduction, fulfilment of regulatory requirements, better ethical practice, natural resource preservation, enhanced public image and as a consequence competitive advantage.

Manufacturing clearly has a major role to play in the move towards a more sustainable society. Sustainability and Sustainable Development (SD) 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 (Elkington, 1997; Lovins et al., 1999; Jovane et al., 2008). This research focuses on the environmental dimension and considers technology as a means of reaching sustainability objectives. Social and economic aspects are positive side-effects of the environmental activities undertaken in the industrial system.

A wide range of tools and approaches already exists to assess and manage the environmental impact of industrial activities and in turn support the integration of sustainability concepts in corporate practice. These tools can be found in various areas such as Industrial Ecology (IE), Cleaner Production (CP), Pollution Prevention (P2) and Sustainable Manufacturing (SM). Those fields of research are contributing to change the way products are manufactured and the way services are provided to customers (Graedel, 1994; Ayres and Ayres, 2002; Robert et al., 2002; Allwood, 2005; Seliger, 2007). However, current practice to improve the environmental performance of industrial activities does not always draw from this academic research.

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. This perspective on building services, manufacturing operations and facilities has been acknowledged by other authors (Hesselbach et al., 2008; Herrmann and Thiede, 2009; Ball et al., 2009). 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 tend to operate in isolation and focus on local rather than system level improvement. Manufacturers need a practical approach to apply the ideas developed in SD, IE and CP to their production system and improve the environmental performance in a systematic way at factory level. Recently published papers have explored modelling as a support for sustainable manufacturing (Heilala et al., 2008). The use of discrete event simulation, energy management systems and manufacturing execution systems can help improve the interaction between production and building systems (Michaloski et al., 2011). Published work demonstrates the potential and challenges in these areas but lacks approaches to bring them together.

IE is a well-documented approach with numerous examples of application at inter-enterprise level (Ayres and Ayres, 2002; Ehrenfeld and Gertler, 1997; Graedel and Howard-Grenville, 2005). Its key feature lies in the integration of various components of a system to reduce its net resource input as well as pollutant and waste outputs. It appears clear that IE has potential to integrate the three main components of a manufacturing system at factory level but this is absent from the literature.

This paper presents a qualitative conceptual model to view a factory unit as an ecosystem. This manufacturing ecosystem model can provide the foundations for developing a quantitative tool to support the identification of environmental performance improvement opportunities across the breadth of the factory including operations, facilities and buildings. The novelty of the model is the detail of IE within the factory unit and the inclusion of these factory elements that are typically considered separately. The model integrates the flows of resources spanning the disciplines of manufacturing engineers, energy and facility engineers, building architects, etc. This ecosystems view of a factory can be used to build cross-disciplinary models of the material, energy and waste (MEW) flows linking the manufacturing operations, the supporting facilities and the surrounding buildings. Given the lack of integration between existing tools, the difficulty lies in selecting the most appropriate ones (Baumann and Cowell, 1999; Finnveden and Moberg, 2005), coping with their complexity (Ahroth et al., 2011) and finding an architecture on which to connect them.

## 2 Methods

This exploratory research is composed of three main steps as shown in Figure 1.

The first step in the research process was to explore current research and knowledge in the area of industrial sustainability, and current environmental activities in industry. The literature was selected using keywords such as “sustainable manufactur\*”, “environmentally conscious manufactur\*”, “green manufactur\*”, “clean production”, “industrial ecology”, “pollution prevention”, etc. In particular, major works and papers by pioneers in those areas of research were selected for the literature review. State-of-the-art in the field of SM was reviewed both for theories and practices. Sources included books on IE, SM, waste management, as well as governmental and academic websites on energy (or more generally on resource) efficiency and examples of best practice. More sources included academic journals such as Journal of Cleaner Production, International Journal of Production Research, etc.

For the second step, the literature was critically reviewed to identify gaps in research. Reported practice was analysed to understand if these gaps were being addressed in industry. The gaps between conceptual approaches, available models and practice were used in the next step.

As the third step, a qualitative conceptual model was developed to fill those gaps to apply the environmental principles industrially. This model is strongly based on IE and SM applied at factory level (intra-enterprise activities). The focus is on overall performance of manufacturing systems using a model of MEW process flows to link all three components of the system: the manufacturing operations, the supporting facilities and the surrounding buildings.

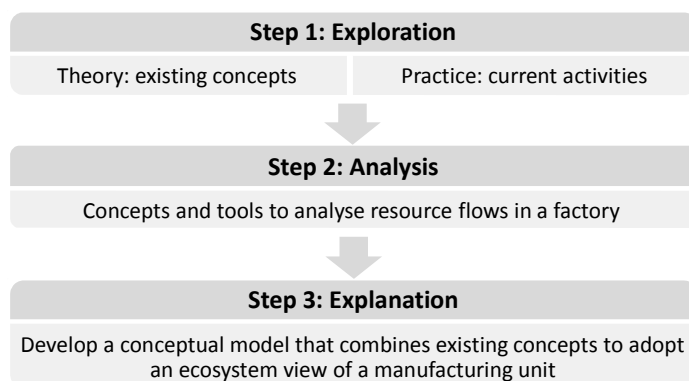


Figure 1. Steps in research method

## 3 Sustainable Manufacturing: Exploration and Analysis

Improving environmental performance in the manufacturing sector means decoupling economic performance from the environmental burden of human activities. 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 the classic economic considerations. 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 (Despeisse et al., 2011). The absence of knowledge on what the drivers and mechanisms are to implement sustainable manufacturing practices can only hinder the wider adoption of the improvements achieved by some manufacturers. Moreover, the literature shows that most efforts focused on product design, individual production technologies, supply chain and product end-of-life management rather than production systems. This section presents the findings of the first two steps of the research (exploration and analysis) by examining industrial systems, then manufacturing systems and finally the available tools to analyse them.

### 3.1 Resource Management and Industrial Ecology

It is important to take a wider perspective on manufacturing systems improvement if it must successfully impact overall environmental performance. A key concept to achieve an ecosystem view is Industrial Ecology (IE). It is defined as the study of interactions and interrelationships both within industrial systems and between industrial and natural systems (Graedel, 1994; Ayres and Ayres, 2002; Frosch and Gallopoulos, 1989; Jelinski et al., 1992). According to Graedel, the three IE model types include:

- Linear resource flows in "Type I" ecology where the system has a strong dependency on external resources and sinks as it assumes the environment has unlimited capacity to produce resource inputs and assimilate waste outputs;
- Quasi-cyclic resource flows in "Type II" ecology where there is a certain degree of cycling in resource circulation through the system which reduces the need for external resource input and waste output;
- Cyclic resource flows in "Type III" ecology which has the highest degree of cycling (self-sufficiency) with closed-loop circulation of resources within the system and the sole input for the system to be sustained is (solar) energy.

At a lower level, the industrial ecosystem (technosphere) is composed of actors which allow resources to circulate through the system and encourage cyclic resource flow so that the flows within the system are larger than the external flows, i.e. resource input and waste output (Graedel, 1994).

IE uses the biological analogy to promote cyclic economy and synergic interactions between industrial and environmental systems (technosphere or anthroposphere, and ecosphere). Such analogy promotes the systematic conversion of waste outputs into resource inputs either within the technosphere as technical nutrients or back to the ecosphere as biological nutrients (McDonough and Braungart, 2002). The concept of IE has evolved over the last 20 years: it started as society-wide (global) to regional with industrial park (macro-level) and finally to company and technology (micro-level) (Andrews, 2001; Zvolinschi et al., 2007). IE analyses systems which can vary greatly in size and nature: the "system" can be a product, a process, a material, a region or a country (Deutz, 2009). There has also been a rapid development of tools associated with IE and other concepts such as CP, P2, etc. The boundaries between those concepts are difficult to draw as they often overlap. Some argue they can also conflict and contradict each other at times, and there is a lack of integration between existing tools for the application of these concepts (Baumann and Cowell, 1999).

As identified above, IE can be applied at multiple levels. Various authors argue that more attention should be placed on the study of interactions within a firm (individual humans) and "direct additional effort to *behavioral* topics" (Andrews, 2001). Other approaches to IE at micro-level promote the inclusion of CP and P2 (Basu and Van Zyl, 2006) or the combined use of thermodynamics and IE perspective of industrial processes to move from a linear to a closed-loop system (Valero et al., 2010). Whilst there are numerous examples of IE at inter-firm level there are surprisingly few at the micro-level which misses the opportunity to continue the biological analogy of resource flows at intra-firm level.

By looking at industrial systems at a regional or global level one might overlook possibilities to improve individual entities of the system from within as it only looks at opportunities for synergetic exchange of resources with other entities (external to the company). IE promotes local use of resource to minimise the need for imports and exports of resource over long distance, and thereby significantly reduce the environmental impact of the product or service produced.

Using the micro-level of IE, an ecosystems view of the factory can be adopted to look at interactions of components within a manufacturing system by focusing on the resource flows between them. The application of an IE perspective has potential to identify resource productivity improvements that positively impact the environmental performance of a manufacturing system. Although this is reductionist if looking at the whole industrial systems (global scale) it does consider manufacturing in a holistic way. Importantly it is at a level where the behaviour of individual humans can be incorporated and closed-loop circulation of resource can be encouraged by taking the shortest path to retain value.

The analysis could focus on individual technologies and examine how to improve the operation of resources or replace them with alternative technologies. Alternatively modelling could place greater emphasis on how those individual resources interact. An analogy can be made with lean manufacturing here. Individual operations can

be improved using lean techniques, e.g. through the application of quick changeovers to reduce the level of downtime and enable more frequent production changes. But more significant benefits are frequently found in examining the flow and interaction between operations, e.g. reducing the level of work in progress to reduce lead time and reduce the possibility of waste through inappropriate or defective stock being created. The same thinking can be applied to modelling of process flows to reduce environmental impact. For example, examining the supply network of compressed air or steam and comparing them to the demand for these supplies to assess whether equipment is oversized rather than simply monitoring for losses in circuits. As with lean, the focus moves from improving energy efficiency of individual processes to improving net energy flow through the factory. To develop this idea further it is necessary to examine the sustainable manufacturing literature.

### 3.2 Sustainable Manufacturing

The manufacturing industry has traditionally been considered 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 concept of industrial ecosystem presented by Frosch and Gallopoulos established a ground for SM (Frosch and Gallopoulos, 1989). Early work in SM was mainly done under the name of IE, P2 and CP. Only recently it became a field of study on its own by combining those themes.

One of the first identified forms of SM 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, and 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 included 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). This approach takes specific material processing and manufacturing operations, and considers individual manufacturing steps in order to decrease their environmental impact independently. In the same period of time, another interpretation of ECM was made and three dimensions to ECM strategies were identified (product, process and technology). These ECM strategies focus on product supply-chain and constitute the famous *recovery* ‘Rs’: reduction, remanufacturing, recycling and reuse (Sarkis and Rasheed, 1995; Sarkis, 1995). The expression *sustainable manufacturing system* began to be used later and was associated with the basic approach of closed-loop circulation of material (Kumazawa and Kobayashi, 2003; Kondoh et al., 2005). Later work in the field of SM focuses largely on design for disassembly, reverse logistics and remanufacturing (Westkämper et al., 2001; Seliger, 2001; Sarkis, 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. The authors argue that this closed-loop approach must be taken in every phase of the product life cycle and not only at the end-of-life. In this research, the focus is on the resource flows in a manufacturing unit, from input as matter or energy to product and waste (both in material and energy form). The main role of industrial systems is to transform those inputs into economically valuable outputs by using efficient technology and processes. In the case of SM, efficiency is not only defined by the cost of the transformation process, but also by its social and environmental impact.

The Technology-Environment paradox 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 SD (Lovins et al., 1999; Jovane et al., 2008). Seliger puts it another way and argues that the manufacturing industry is responsible for the environmental efficiency of our society and technology (Seliger, 2007). Our definition of efficient manufacturing follows this idea: the efficiency of a manufacturing system is defined by the overall resource input against the overall waste or pollutant output. Thus a system with internal reuse of waste can be more efficient than a system which purely focuses on the ratio of output over input of individual processes and fails to consider waste as a resource. In other words, internal reuse of waste increases the efficiency of the manufacturing system and reduces the environmental impact through resource depletion and pollutant emissions.

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 (Bhamra, 2004; Rahimifard and Clegg, 2007; 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 (Ehrenfeld and Gertler, 1997; Graedel and Howard-Grenville, 2005), 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; Sarkis, 2003; Beamon, 2008) 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 (Lovins et al., 1999; Allwood, 2005; Despeisse et al., 2011; Abdul Rashid et al., 2008).

In order to develop a conceptual model using IE and sustainable manufacturing principles an appreciation of available tools to provide quantitative analysis is first necessary.

### 3.3 Analytical and Improvement Tools

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

- 1) Assessment, monitoring and inventory tools
- 2) Engineering, design and improvement tools
- 3) Environmental policies and enforcement tools
- 4) Prioritisation, management and decision-making tools

Selection of the appropriate tools must take into consideration the object of study and the types of impacts of interest (Finnveden and Moberg, 2005). Here we looked at the environmental performance of manufacturing systems; therefore tools from the categories 1 and 2 were investigated.

For example, Life Cycle Assessment (LCA) is a fundamental tool (category 1) for evaluating 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. As with 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 those of competitors by making “convenient” assumptions. Some rigorous methodologies for simplified LCA have been introduced to avoid such misuse of the tool (Mori et al., 2000).

Another example from category 2 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). The earlier the integration of environmental thinking is done, the more effectively the environmental impacts of a product can be reduced (Keoleian and Menerey, 1994; Müller et al., 1999). Similar concepts are Design for Assembly, Design for Disassembly and Design for Recycling, which are often referred to as Design for X strategies or DfX.

Existing tools for environmental performance evaluation and improvement are well developed, but they do not provide a systematic methodology for manufacturers to find solutions within their factory. For instance the two examples given above, LCA and DfE, are powerful tools, 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 to 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.

Tools from categories 2 and 3 are crucial to promote and encourage the implementation of environmental performance improvements but are insufficient to use in their current form for modelling the resource flows at a factory level, failing to offer a process rather than product perspective. Use of existing tools alone is insufficient to analyse a factory as a combined operations, facilities and buildings ecosystem. We suggest that first models must be created to conceptualise and later analyse the manufacturing system, only then work on identifying opportunities and implementing integrated solutions can be started. In support, companies could use their

environmental management systems (EMS) and ISO14001 standard to manage the outcome of the modelling to help them meet the targeted level of environmental performance.

### 3.4 In Summary

This section has reviewed the IE, SM and tools literature. There are significant gaps in the application of IE at factory level with little or no published work on how to achieve this. The body of sustainable manufacturing literature is growing but tends to focus on the efficiency of technology or individual processes rather than overall resource efficiency. Lastly, when examining tools and techniques, there is little to support sustainable manufacturing concepts using a systems view of the factory. The contribution of the work that follows here is to address these gaps through the development of a conceptual ecosystem model of the factory.

## 4 Development of the Conceptual Model

### 4.1 Conceptual Model Rationale

The literature review investigated well-established areas such as IE, CP, P2, as well as SM which is a recent and rapidly growing field. There are numerous concepts and tools for assessing and improving the performance of production systems but there are no models used by manufacturers for systems wide improvement of their environmental performance. The rationale for developing the concept model is described in this section with reference back to the literature reviewed earlier as appropriate.

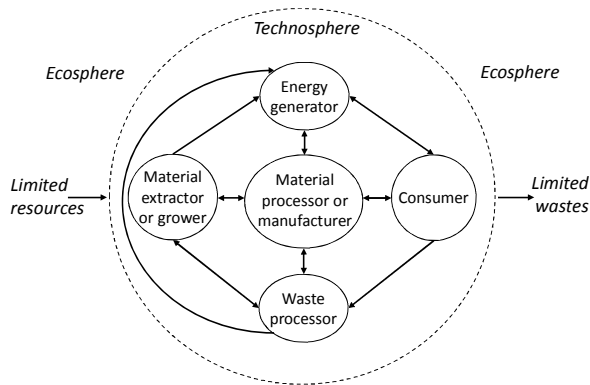
Few industries have considered their manufacturing system as an ecosystem inspired by a biological model where material and energy are used not only in an efficient way, but also in an effective way. By following process flows with a system view, it is possible to identify solutions to reduce environmental impact while generating economic savings. The approach presented in this paper combines various sets of strategies or principles for industrial sustainability (Lovins et al., 1999; Allwood, 2005; Abdul Rashid et al., 2008) and includes the recurring themes 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 measures to increase the efficiency with which resources 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.

### 4.2 Industrial Ecology as Concept Foundations

In order to reduce or limit the environmental impact caused by human activities, it is necessary to increase the efficiency with which resources are “consumed” in the technosphere. Figure 2 was adapted from IE industrial ecosystem and “type II” of IE model (Graedel, 1994) to show how material as well as energy is flowing between system’s components in the technosphere, thus the *energy supplier* or *energy generator* has been added to the original IE model. Other players in the industrial system such as water and chemicals supplier are not represented and assumed to be included in the *material extractor* or *material grower*. Moreover, this representation presents the manufacturer as the central element. At each step of the material or energy flow life cycle, some losses and pollution occur due to limits of efficiency in resource conversion. Pollutant emissions from energy in manufacturing can be either direct (gas combustion in boiler on-site for heating) or indirect (fuel combustion from off-site electricity generation). Pollutant emissions are not shown in the figure below since it focuses on the flows rather than on their impacts. Other environmental impacts, such as resource depletion, need to be taken into consideration to quantify the consequences of manufacturing activities on the environment.

By maximizing resource productivity and closing the loop of resource circulation within the technosphere, natural resources can be preserved and the amount of waste output and related emissions can be minimised. This model was used as the foundations to establish the perspective for the direction of change needed towards a sustainable society by increasing this resource productivity through the recirculation of what was previously “lost” or “emitted” to the ecosphere.



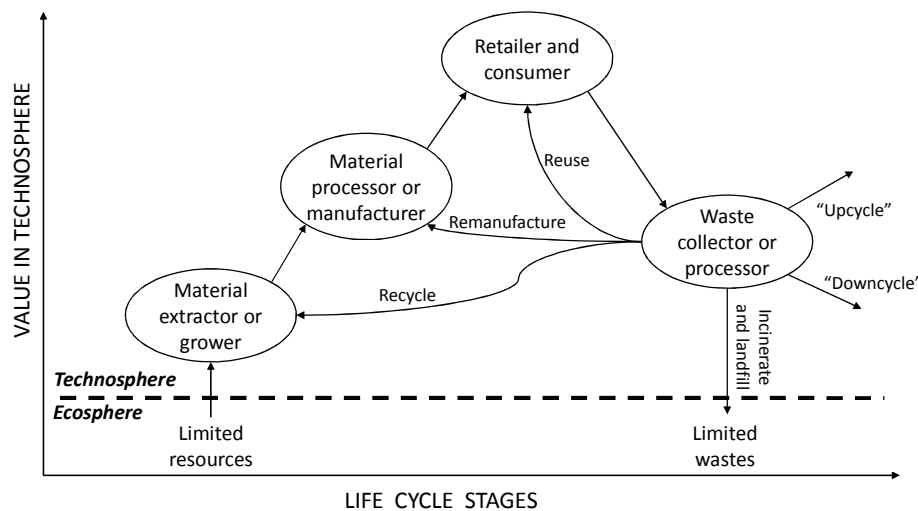
**Figure 2. Type II industrial ecosystem model focused on the manufacturer** (Despeisse et al., 2009)

Figure 2 illustrates the system approach with a clear boundary between ecosphere (associated with environmental science) and technosphere (sometimes called human-sphere or anthroposphere, associated with environmental engineering). However the distinction between technosphere and ecosphere is blurred in reality as the technosphere is embedded inside the ecosphere and the interactions between the two are ever increasing. Flows of material, energy and waste are all considered as resources or technical nutrients while they remain within the boundaries of the system, but they should be considered separately due to their different nature and role. Whilst both material and energy are traditionally viewed as resources for the system, waste is also a potential resource which needs particular attention as it is often overlooked. Additionally, the separation allows distinction between resource inputs and resource outputs to individual system components, as well as recognising energy as a distinct flow in Type III model of IE.

#### 4.3 Value in Resource Life Cycle

Ricoh's Comet Circle concept illustrates how closed-loop can be achieved taking various paths at products' end-of-life (RICOH, 1994). The value of material through its life-cycle can be represented as shown in Figure 3 where the material cycle stages (Allwood, 2005) are represented by the actors corresponding to components industrial ecosystem model (see adapted model from Graedel in Figure 2). For example, *Material extraction* is done by the actor *Material extractor or grower*; *Material processing*, *Component manufacturing* and *Assembly* by the *Material processor or manufacturer* which is the actor the study focuses on, etc.

This material life cycle model shows the embedded value of material flow which is conceptually described as the economic value (sometimes associated with the thermodynamic state) of material as it enters the technosphere and is converted from raw form into finished products (i.e. economically valuable goods) before deteriorating in use. Energy is consumed to bring material to the next stage whether it is adding value or not. The material life cycle model also shows how the embedded value can be retained in the technosphere by closing the loop using the shortest path: following product use, more energy must be used to recover the value of material when going back further in the life cycle. Other paths for material are possible to give it a second life by creating an even more valuable product (upcycle) or a product that still retains some value (downcycle). This value based view will encourage local reuse of material and energy rather than distance reuse, hence the resolution of IE at factory level becomes important.



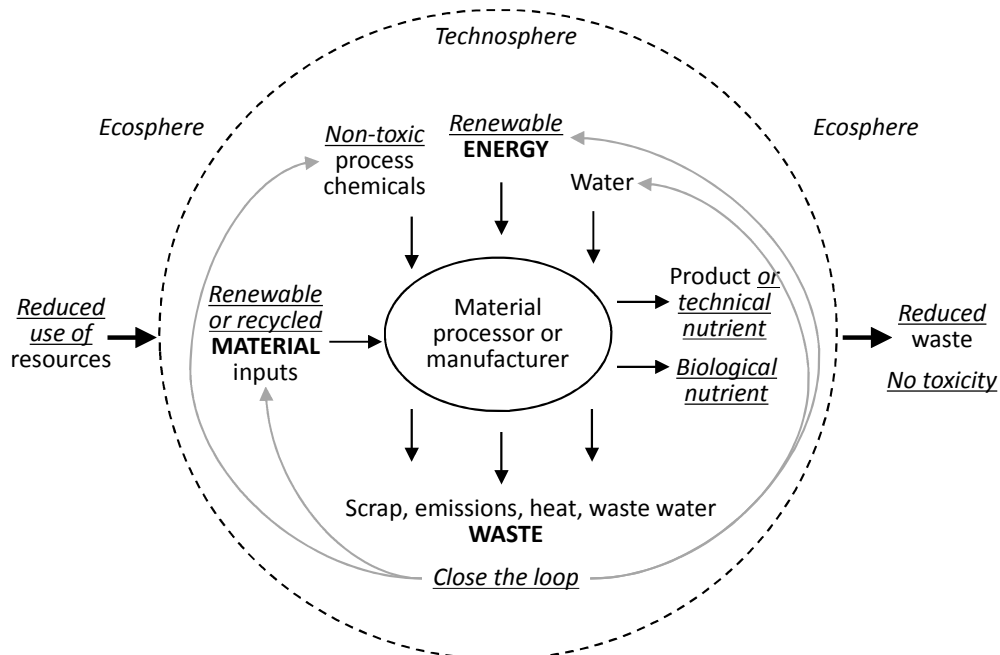
**Figure 3. Resource life cycle: value added in the industrial ecosystem**

#### 4.4 Ecosystems View at Factory Level

The main actor of concern here is the *manufacturer* (or manufacturing system). It is composed of three components: the manufacturing operations, the supporting facilities and the surrounding buildings (Hesselbach et al., 2008; Herrmann and Thiede, 2009; Ball et al., 2009).

In the case studies found on sustainable manufacturing (Despeisse et al., 2011), the system boundaries varied from gate-to-gate to cradle-to-grave. Focusing on the factory (gate-to-gate analysis), it is necessary to capture the energy and material networks that link the manufacturing system's components, namely production, facility and building systems. The external actors are, for example, material and parts suppliers, physical waste collection and treatment companies, regional energy supply systems, European electricity markets, taxes, fees and other means of control. These external actors and activities occurring off-site are not the focus here as they are typically beyond the control of the factory. There are exceptions to this for the impact assessment where the environmental impact caused by the energy used on-site (but generated off-site) is included.

Technologies, i.e. the means by which humans are interacting with the natural environment and transforming natural resources, can support manufacturers to approach SM but which technologies should be used? How are these technologies linked together? A systems view of a factory will encourage fundamental analysis. Accounting for the MEW flows across the whole system as illustrated in Figure 4, it goes beyond switching to clean sources to meet current energy and material demand while reducing environmental burden. Therefore it moves away from this simple substitution of energy supply to thinking in a more integrated way and focusing on improving the utilisation of resources within the system. The material and energy flows cover the domains of process engineering, facility and building design and management. Consequently the flows can be jointly studied by different departments or areas of the factory to identify waste and opportunities to reduce waste by integrating flows rather than addressing the individual wastes in the respective fields. From an organisational perspective, performance measurement systems need to be modified to support such collaboration. Among other barriers to the adoption proactive behaviour (Murillo-Luna et al., 2011), typical ownership and associated metrics of key resource flows can act as barriers to engineers from different domains gaining credit for reduction activities.



**Figure 4. Manufacturing ecosystems model: from linear to quasi-cyclic resource flow through a process or system**

Manufacturing processes cannot be “zero carbon” or “zero waste” alone but when viewing such processes as part of a wider system it is possible to achieve net carbon reduction or closed-loop circulation of wastes. Thus it demands particular attention to potential process interactions and not to isolated technologies or utilities (Ball et al., 2009); else the approach will offer little advance over traditional tools in addressing the pollution problems (such as end-of-pipe solutions) rather than the source of the problems (such as pollution prevention and precautionary principle).

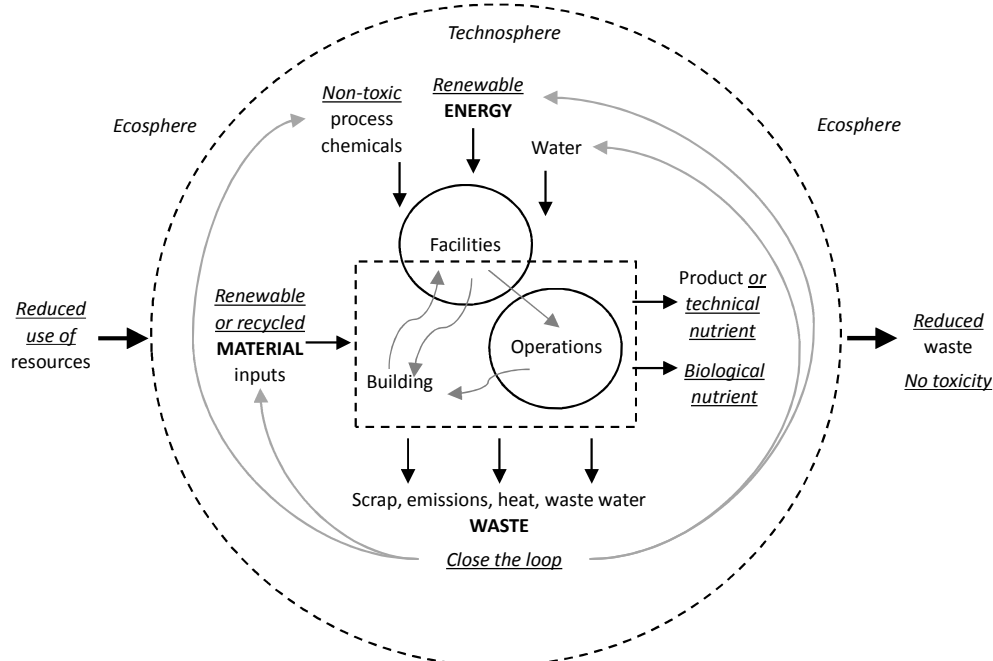
#### 4.5 Modelling Manufacturing Systems

The data analysis should focus on the resource flows linking the system components and on how technologies are consuming and transforming the flows to create process maps of the manufacturing system. As in an ecosystem, the importance is the overall productivity of resources and how they circulate in the system (see



Figure 4) rather than the efficiency of individual processes or technologies. This advances current literature that typically focuses on substitution of technology or resource inputs (renewables) rather than looking at overall resource-use inefficiencies (including simple equipment management approaches) and possibilities to create synergies within the system by reusing waste from one process as an input to another (as in pinch analysis). The analysis needs to be carried out with a process mindset to deliver an integrated process view of the factory. From these process maps of a manufacturing enterprise the MEW flows can be documented. This approach captures the complexity and the interactions between the three components (operations, facilities and buildings as shown in Figure 5) to enable better understanding of it.

By capturing the MEW process flows systemically, potential interactions between processes can be identified to recover material and energy losses, “capture” them and use them in another process. 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 as a support for sustainable manufacturing (Heilala et al., 2008). The use of discrete event simulation, energy management systems and manufacturing execution systems can help improve the interaction between production and building systems (Michaloski et al., 2011). Such work has demonstrated the capability of modelling in principle but is as yet not supported by an overall integrating modelling concept.



**Figure 5. Manufacturing ecosystem model with the three components and MEW flows**

By taking a systems view, we acknowledge that everything affects everything else and therefore we need a tool which helps anticipating those effects while allowing the identification of long-term consequences and root causes. Using a process modelling approach to map MEW flows and analyse them can highlight opportunities to use outputs from some activities as inputs to others to reduce net consumption. Such principles for recovery and reuse of waste and energy, and therefore reduction of cost and environmental impact could be applied across a whole facility. The conceptual model presented in Figure 5 can be used to develop quantitative modelling tools to support such improvement activities.

The approach would be used to improve manufacturing practices with technical and organisational measures (physical change or a management improvement of equipment/process or resource flow). These measures aim to increase the efficiency with which resources are transformed into economically valuable goods and create closed-loop circulation of resources within the manufacturing system by identifying opportunities in connections between processes of the three components, i.e. the manufacturing operations, the supporting facilities and the surrounding buildings which are linked by MEW resource flows.

#### 4.6 Towards a Manufacturing Ecosystem Modelling Tool

Using the manufacturing ecosystem conceptual model the elements represented are the buildings, the technology components (equipment and processes) placed in and near the buildings, and the resource flows linking the technology components and buildings. All elements of the model are characterised by process data which can be design data for fixed characteristics (equipment size, capacity, efficiency, running load, etc.) or metered data for

the dynamic flows (inputs: energy and material including water and chemicals; outputs: product and wastes including physical waste accumulating in bins as well as energy waste mostly in the form of heat).

This approach provides a base on which to build models, e.g. Figure 6, to identify improvement opportunities in resource productivity by analysing the MEW flows and, importantly, their timing through a manufacturing system. The figure represents the factory building and offices, the operations system composed of processes, and the facilities supporting those processes and the building system. The type of improvement can be organisational/operational management or technical/physical change, and the elements targeted are resource flow or technology component. The generic examples below cover various MEW flows or technological solutions to identify improvements by using simple rules based on the recurring themes for industrial sustainability presented in the previous section (adapted from Lovins et al., 1999; Allwood, 2005; Abdul Rashid et al., 2008).

- Resource input (prevention): eliminate unnecessary elements to avoid usage at the source, stop or stand-by process when not in use. For instance, Facility 3 can be switched off when there is no product in Process 1.
- Waste output (waste reduction): good housekeeping practice, repair and maintain equipment to reduce waste generation. Prevent leakage or heat loss in the hot air circulation system (Facility 1) or in the hot water supply network (Facility 2).
- 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. Facilities 1, 2, and 3 do not need to be running full load; they can be tuned down to match the demand of Process 1 without excess energy and meet the minimum set points for the conditioning air in the Offices.
- 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. Reuse the waste heat from Facilities 1, 2, 3 and Processes 1, 2 for heating the Offices.
- Replace input or technology components (substitution): renewable and non-toxic inputs, change the way the function is achieved to allow larger scale improvements.

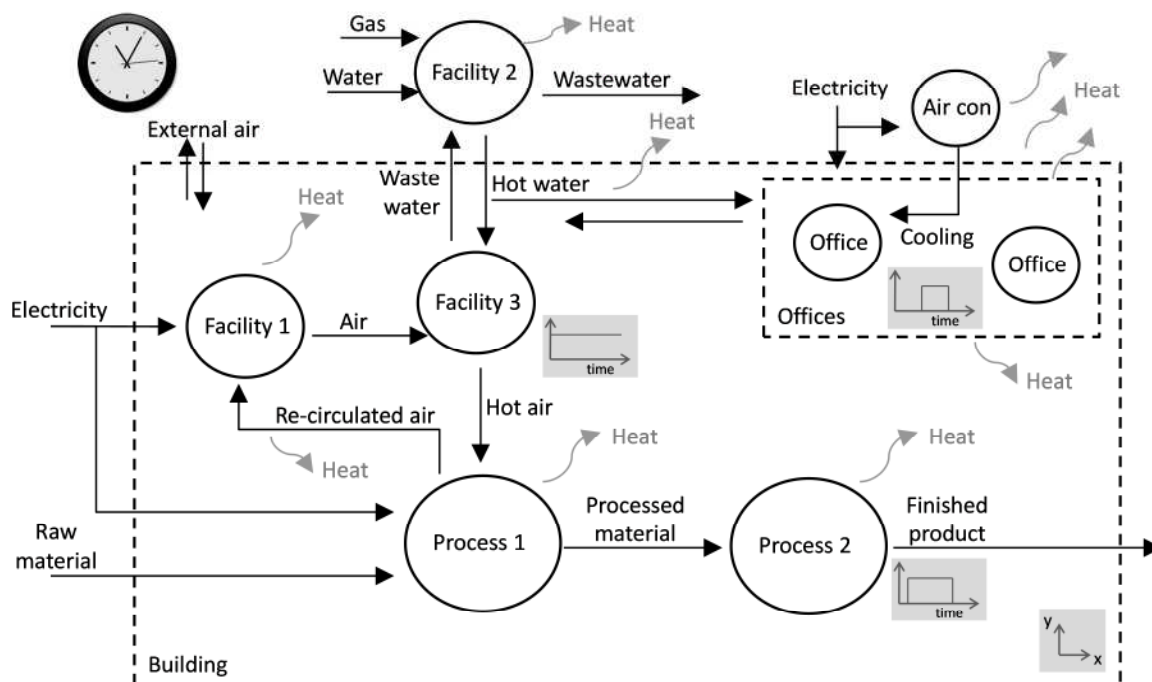


Figure 6. Manufacturing ecosystem example, snapshot at a specific time during operations.

## 5 Discussion

While the concepts of SD have become increasingly known in academic theory and industrial practice, there are still different interpretations of what a sustainable level of performance is. In the same way P2, CP and IE have gained importance over the last decade but still need to be strengthened to ensure success in their application in industry. Looking back at the historic evolution of these concepts, clear and strong definitions are a key factor in

their diffusion among practitioners (whatever the theoretical gains of their application are). For instance, although P2 has been recognised as a better approach than pollution control and other end-of-pipe solutions for long-term results, it has been less successful than pollution control practices. The reason for this limited popularity of P2 compared to pollution control is the never-ending debate on its definition: pollution control is a clearer concept and associated with strong command-and-control policies, and is consequently easier to apply (Oldenburg and Geiser, 1997).

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 (rebound effect). Activities in the newly developed field of SM can be found under the label of sustainable production, competitive sustainable manufacturing, environment conscious manufacturing, environmental benign manufacturing, environmentally responsible manufacturing, etc. But this semantic confusion due to multiple labels for similar concepts and vagueness in the definitions can be one of the main barriers to their success as demonstrated for P2.

Another debated area is the system boundary definition as it has implications regarding the accounting method. For instance, carbon-neutral energy system usually means that there is no direct CO<sub>2</sub> emission during the use phase of the energy system. Renewable energy sources are examples of carbon-neutral energy systems. Biomass however is considered to be carbon-neutral through the fact that growing the fuel captures as much CO<sub>2</sub> as it releases during its combustion. But taking a life cycle perspective, CO<sub>2</sub> emissions occur during manufacturing, commissioning, maintenance, and decommissioning; those are often ignored when assessing the carbon footprint of renewable energy systems.

The analysis focused solely on the manufacturing system, including the manufacturing operations, the supporting facilities and buildings. The boundaries correspond to the factory gates with accounts for direct emissions on-site as well as indirect emissions resulting from energy use. The emissions due to material use are not included as they are already being accounted for by the resource extractor, processor and supplier (avoid double counting). The authors recognise the importance of a larger perspective on industrial systems to optimise resource use (Ehrenfeld and Gertler, 1997; Baumann et al., 2002) and the need for a life cycle view on manufacturing activities to achieve environmental sustainability. However, the research focus has been narrowed down to the study of a single manufacturing site in order to change the level of application of concepts such as food-web, industrial metabolism or industrial ecosystem (closed-loop circulation of resource). These are traditionally applied at macro-level, involving various industrial entities and local communities, and have been extensively treated in the literature and their application demonstrated in several regions. As the model developed addresses manufacturers, it was oriented towards elements on which they have full control and shortest potential feedback loops. Thus the boundaries of the system are drawn around the manufacturing site and stop at the factory gates.

This research feeds into a long-term project to build a modelling tool and improvement methodology. The modelling tool would account for the quality, location and timing of the resource flows in the manufacturing ecosystem model which cannot be evaluated easily by static flow diagrams. In this paper a qualitative modelling approach was presented. Further work in quantitative modelling, including data collection, simulation, implementation and environmental performance assessment (improvement methodology) needs to be carried out to quantitatively assess benefits. In an ecosystem, all elements are put together in order to constitute a synergetic system with the emphasis being that the whole is more than the sum of individual parts. Modelling the MEW flows gives the opportunity to find compatible input and output flows between processes. It is necessary to develop simulation capabilities which can model the manufacturing system using the MEW process flows, simulate the model to estimate (and predict) its environmental and economic performance, and finally suggest potential improvements.

## 6 Conclusions

As shown by many case studies, it is possible to decouple economic profit and environmental degradation. This paper has introduced a conceptual model to underpin a shift from environmental improvement in terms of performance *per unit produced* to an overall resource-use and pollution reduction. Consequently, it draws the attention towards the overall behaviour of the system and provides a guide to make improvements.

A conceptual factory ecosystems model has been proposed. A factory unit perspective was adopted to develop the foundations of a tool for manufacturers to improve their activities. The research focuses on resource flows to identify potential connections where the outputs of some activities could be used as the inputs elsewhere in the system rather than treated as losses or wastes leaving the system.

The move towards sustainability will require changes on many levels: not only production methods must be more respectful ethically and environmentally, but consumption patterns must also be changed. This research supports the move to reduce the environmental impact of manufacturing through the reduction of resource consumption, waste generation and pollutants emission by improving resource productivity and closing the flow

of MEW at the factory level. But this is only one piece in the jigsaw puzzle of SM which itself is only a part of a more global and multidisciplinary solution for a sustainable society.

The academic contribution to knowledge of this research has been to provide an understanding of how an ecosystems view can be a basis for more environmentally sustainable manufacturing activities. By considering the IE concepts with a manufacturer perspective, integrating the MEW flows through a manufacturing system has proved possible the adoption of an ecosystems view on manufacturing activities.

The novelty in the approach presented in this paper is the intra-enterprise level view of IE. By tracking the MEW flows throughout the manufacturing systems, the link between operations, facilities and buildings is made. In turn, this integrated view allows the identification of wasteful activities where virgin inputs can be substituted by a wasteful or unwanted output generated elsewhere in the system.

## References

- Abdul Rashid, S. H., Evans, S., Longhurst, P., 2008. A comparison of four sustainable manufacturing strategies. *International Journal of Sustainable Engineering* 1(3), 214-229.
- Ahlroth, S., Nilsson, M., Finnveden, G., Hjelms, O., Hochschorner, E., 2011. Weighting and valuation in selected environmental systems analysis tools – suggestions for further developments. *J Clean Prod* 19(2-3), 145-156.
- Allenby, B. R., 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.
- Andrews, C. J., 2001. Building a micro foundation for industrial ecology. *J Ind Ecol* 4(3), 35-51.
- Ayres, R. U., Ayres, L. W. (eds.), 2002. *A Handbook of Industrial Ecology*, Edward Elgar Publishing, Northampton, MA.
- 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., Wilson, H., 2007. State-of-the-art in product-service systems. *Proc Inst Mech Eng Part B J Eng Manuf* 221(10), 1543-1552.
- Ball, P. D., Evans, S., Levers, A., Ellison, D., 2009. Zero carbon manufacturing facility – towards integrating material, energy, and waste process flows. *Proc Inst Mech Eng Part B J Eng Manuf* 223(9), 1085-1096.
- Basu, A. J., Van Zyl, D. J. A., 2006. Industrial ecology framework for achieving cleaner production in the mining and minerals industry. *J Clean Prod* 14(3-4), 299-304.
- Baumann, H., Boons, F., Bragd, A., 2002. Mapping the green product development field: engineering, policy and business perspectives. *J Clean Prod* 10(5), 409-425.
- Baumann, H., Cowell, S. J., 1999. An evaluative framework for conceptual and analytical approaches used in environmental management. *Greener Manag Int* (26), 109-122.
- Beamon, B. M., 2008. Sustainability and the Future of Supply Chain Management. *Oper Supply Chain Manag* 1(1), 4-18.
- Bhamra, T. A., 2004. Ecodesign: the search for new strategies in product development. *Proc Inst Mech Eng Part B J Eng Manuf* 218(5), 557-569.
- Davis, R. L., Costa, J. E., 1995. Role of ECM in bringing about pollution prevention. *Int SAMPE Tech Conf* 27, 328-330.
- Despeisse, M., Ball, P. D., Evans, S., Levers, A., 2009. Zero Carbon Manufacturing through Process Flow Modelling, *Proceedings of the 11th MITIP conference*, 15–16 October 2009, Bergamo, pp. 565.
- Despeisse, M., Mbaye, F., Ball, P. D., Evans, S., Levers, A., 2011. Emergence of sustainable manufacturing practices. *Int J Prod Planning Control* [forthcoming], 1-23. DOI: 10.1080/09537287.2011.555425.
- Deutz, P., 2009. Producer responsibility in a sustainable development context: Ecological modernisation or industrial ecology? *Geogr.J.* 175(4), 274-285.
- Ehrenfeld, J. R., Gertler, N., 1997. Industrial ecology in practice: The evolution of interdependence at Kalundborg. *J Ind Ecol* 1(1), 67-79.
- Elkington, J., 1997. *Cannibals with Forks: The Triple Bottom Line of 21st Century Business*, Capstone Publishing, Oxford.
- Finnveden, G., Moberg, A., 2005. Environmental systems analysis tools - An overview. *J Clean Prod* 13(12), 1165-1173.

- Frosch, R. A., Gallopoulos, N. E., 1989. Strategies for Manufacturing. *Sci Am* 261(3), 144-152.
- Glavič, P., Lukman, R., 2007. Review of sustainability terms and their definitions. *J Clean Prod* 15(18), 1875-1885.
- Goldstein, D., Hilliard, R., Parker, V., 2011. Environmental performance and practice across sectors: methodology and preliminary results. *J Clean Prod* 19(9-10), 946-957.
- 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., Howard-Grenville, J. A., 2005. *Greening the industrial facility: perspectives, approaches, and tools*, Springer, New York.
- Hart, S. L., 1995. A Natural-Resource-Based View of the Firm. *Academy of Management Review* 20(4), 986-1014.
- Heilala, J., Vatanen, S., Tonteri, H., Montonen, J., Lind, S., Johansson, B., Stahre, J., 2008. Simulation-based sustainable manufacturing system design, *Winter Simulation Conference Proceedings (WSC'08)*, 7–10 December 2008, Miami, FL, pp. 1922.
- Herrmann, C., Thiede, S., 2009. Process chain simulation to foster energy efficiency in manufacturing. *CIRP Journal of Manufacturing Science and Technology* 1(4), 221-229.
- Hesselbach, J., Herrman, C., Detzer, R., Martin, L., Thiede, S., Lüdemann, B., 2008. Energy efficiency through optimized coordination of production and technical building services, 17–19 March 2008, Sydney (Australia), .
- Hibbitt, C., Kamp-Roelands, N., 2002. Europe's (mild) greening of corporate environmental management. *Corp Environ Strat* 9(2), 172-182.
- Jawahir, I. S., Rouch, K. E., Dillon Jr., O. W., Holloway, L., Hall, A., 2007. Design for sustainability (DFS): New challenges in developing and implementing a curriculum for next generation design and manufacturing engineers. *Int J Eng Educ* 23(6), 1053-1064.
- Jelinski, L. W., Graedel, T. E., Laudise, R. A., McCall, D. W., Patel, C. K. N., 1992. Industrial ecology: Concepts and approaches. *Proc Natl Acad Sci USA* 89(3), 793-797.
- Jovane, F., Yoshikawa, H., Alting, L., Boër, C. R., Westkämper, E., Williams, D., Tseng, M., Seliger, G., Paci, A. M., 2008. The incoming global technological and industrial revolution towards competitive sustainable manufacturing. *CIRP Ann Manuf Technol* 57(2), 641-659.
- Keoleian, G. A., Menerey, D., 1994. Sustainable development by design: Review of life cycle design and related approaches. *J Air Waste Manag Assoc* 44(5), 645-668.
- Kondoh, S., Nishikiori, Y., 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., 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.
- Lakhani, M., 2007. The need for Clean Production and Product Re-design. *J Clean Prod* 15(13-14), 1391-1394.
- Lovins, A. B., Lovins, L. H., Hawken, P., 1999. A road map for natural capitalism. *Harv Bus Rev* 77(3), 145-158.
- Matten, D., Crane, A., 2005. Corporate citizenship: Toward an extended theoretical conceptualization. *Acad Manag Rev* 30(1), 166-179.
- McDonough, W., Braungart, M., 2002. *Cradle to cradle : remaking the way we make things*, North Point Press, New York.
- Michaloski, J. L., Shao, G., Arinez, J., Lyons, K., Leong, S., 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.
- Mont, O. K., 2002. Clarifying the concept of product-service system. *J Clean Prod* 10(3), 237-245.
- Mori, Y., Huppel, G., Udo de Haes, H. A., Otoma, S., 2000. Component manufacturing analysis: A simplified and rigorous LCI method for the manufacturing stage. *Int J Life Cycle Assess* 5(6), 327-334.
- Mouzon, G., Yildirim, M. B., Twomey, J., 2007. Operational methods for minimization of energy consumption of manufacturing equipment. *Int J Prod Res* 45(18-19), 4247-4271.

- Müller, K. G., Court, A. W., Besant, C. B., 1999. Energy Life Cycle Design: A Method. *Proc Inst Mech Eng Part B J Eng Manuf* 213(4), 415-419.
- Murillo-Luna, J. L., Garcés-Ayerbe, C., Rivera-Torres, P., 2011. Barriers to the adoption of proactive environmental strategies. *J.Clean.Prod.* 19(13), 1417-1425.
- Oldenburg, K. U., Geiser, K., 1997. Pollution prevention and...or industrial ecology? *J Clean Prod* 5(1-2), 103-108.
- Owen, J. V., 1993. Environmentally conscious manufacturing. *Manuf Eng* 111(4), 44-55.
- Rahimifard, S., Clegg, A. J., 2007. Aspects of sustainable design and manufacture. *Int J Prod Res* 45(18-19), 4013-4019.
- Richards, D. J., 1994. Environmentally conscious manufacturing. *World Class Des Manuf* 1(3), 15-22.
- Richards, D. J., Allenby, B. R., Frosch, R. A., 1994. The Greening of Industrial Ecosystems: Overview and Perspective, in: Allenby, B. R., 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: <http://www.ricoh.com/environment/management/concept.html> (accessed 02/09/2011).
- 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? *J Clean Prod* 8(3), 243-254.
- Robèrt, K. H., Schmidt-Bleek, B., Aloisi De Lardere, J., Basile, G., Jansen, J. L., Kuehr, R., Price Thomas, P., Suzuki, M., Hawken, P., Wackernagel, M., 2002. Strategic sustainable development - Selection, design and synergies of applied tools. *J Clean Prod* 10(3), 197-214.
- Sarkis, J., 2003. A strategic decision framework for green supply chain management. *J Clean Prod* 11(4), 397-409.
- Sarkis, J., 2001. Manufacturing's role in corporate environmental sustainability: Concerns for the new millennium. *Int J Oper Prod Manag* 21(5-6), 666-686.
- Sarkis, J., 1995. Manufacturing strategy and environmental consciousness. *Technovation* 15(2), 79-97.
- Sarkis, J., Rasheed, A., 1995. Greening the Manufacturing Function. *Bus Horiz* 38(5), 17-27.
- Seliger, G., 2007. *Sustainability in manufacturing: recovery of resources in product and material cycles*, Springer, Berlin.
- Seliger, G., 2001. Product innovation - Industrial approach. *CIRP Ann Manuf Technol* 50(2), 425-443.
- Seliger, G., Kim, H. J., Kernbaum, S., Zettl, M., 2008. Approaches to sustainable manufacturing. *Int J Sustain Manuf* 1(1-2), 58-77.
- Seliger, G., Zettl, M., 2008. Modularization as an enabler for cycle economy. *CIRP Ann Manuf Technol* 57(1), 133-136.
- Srivastava, S. K., 2007. Green supply-chain management: A state-of-the-art literature review. *Int J Manag Rev* 9(1), 53-80.
- Thiede, S., Herrmann, C., Kara, S., 2011. State of research and an innovative approach for simulating energy flows of manufacturing systems, *Glocalised Solutions for Sustainability in Manufacturing - Proceedings of the 18th CIRP International Conference on Life Cycle Engineering*, pp. 335.
- Valero, A., Usón, S., Torres, C., Valero, A., 2010. Application of thermoeconomics to industrial ecology. *Entropy* 12(3), 591-612.
- Westkämper, E., 2002. Platform for the integration of assembly, disassembly and life cycle management. *CIRP Ann Manuf Technol* 51(1), 33-36.
- Westkämper, E., Alting, L., Arndt, G., 2001. Life cycle management and assessment: Approaches and visions towards sustainable manufacturing. *Proc Inst Mech Eng Part B J Eng Manuf* 215(5), 599-626.
- Westkämper, E., Feldmann, K., Reinhart, G., Seliger, G., 1999. Integrated development of assembly and disassembly. *CIRP Ann Manuf Technol* 48(2), 557-565.
- World Commission on Environment and Development, 1987. *Our common future*, Oxford University Press, Oxford.
- Zvolinschi, A., Kjelstrup, S., Bolland, O., Van Der Kooi, H. J., 2007. Exergy sustainability indicators as a tool in industrial ecology: Application to two gas-fired combined-cycle power plants. *J Ind Ecol* 11(4), 85-98.