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ZERO CARBON MANUFACTURING THROUGH PROCESS FLOW MODELLING

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Abstract:

The pressure on natural resources and emerging environmental legislation are leading manufacturers to adopt solutions to reduce their environmental impact, thereby becoming more sustainable, while enhancing competitiveness. Current approaches in this area are fragmented and clustered around technologies rather than around processes that link the technologies together. There is a need to better understand material, energy and waste (MEW) flows, as well as the interaction between processes in a manufacturing facility from a systemic viewpoint. This paper presents an approach using process flow modelling in order to help manufacturers to identify potential improvements to progress towards competitive sustainable manufacturing. Ultimately they could reach zero carbon manufacturing (ZCM) by having zero material resource degradation, zero net energy demand and zero waste across the system.

Keywords: Competitive sustainable manufacturing, zero carbon, modelling, process flows, industrial engineering.

1. INTRODUCTION

Activities to reduce environmental impact have traditionally been associated with increasing operations costs by investing in high-efficiency or cleaning technologies, or purchasing of green electricity. This traditional attitude is focused on short-term results and has long ignored the potential for long-term savings. There is an increasing pressure on material and energy prices and availability as well as emerging environmental legislation. Manufacturers are increasingly proactive in adopting solutions to reduce their material and energy consumption, thereby becoming more sustainable, and in turn potentially reduce production cost and increase competitiveness. But there is still a lot more to be done to reach a sustainable level of activity. Over the last ten years, an increasing volume of literature on the subject has tried to bring answers on countermeasures to tackle global issues in various sectors such as agriculture, industry and transport.

In the area of manufacturing operations, the current approach is fragmented and clustered around technologies rather than around processes that link the technologies together. Beyond technology and product design improvements, few industries have considered their manufacturing system as an industrial metabolism using natural systems as a model [1], [4]. Here material and energy are used not only in an efficient but also an effective way [15] in order to comply with the four system's conditions according to *The Natural Step* [20]:

- Do not deplete natural resources extracted from ecosphere;
- Do not accumulate waste produced by technosphere into the ecosphere;

- Do not degrade the ecosphere by physical means;
- Meet human needs worldwide.

Figure 1 illustrates the system approach with a clear distinction between ecosphere (associated with environmental science) and technosphere (associated with environmental engineering). Material and energy inputs are “consumed” in the technosphere with limited efficiency. By maximizing resource use productivity, the amount of waste output and related CO_2 emissions can be minimised. The approach presented in this paper aims to increase this efficiency by allowing the recirculation of what was previously “lost” or “emitted” to ecosphere. Emissions of CO_2 are used as a performance indicator. They are not shown in the figure below since it focuses on the flows rather than on their impacts. Moreover this indicator does not capture all the environmental impacts such as resource depletion, but it is the easiest measure to quantify the consequences of human activities on environment.

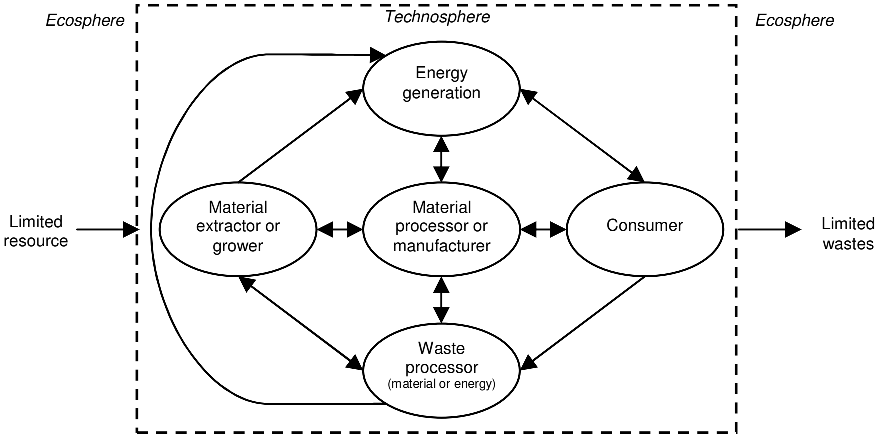

Figure 1: Model used in industrial ecology (adapted from [18], p. 27)

Efficiency gains can have counter-intuitive results if they are not accompanied by policies to control their consequences and to avoid the rebound effect [14] where expected savings are partly offset by increased consumption. Another similar effect is the backfire effect, where the efficiency improvement measures are completely offset and the total energy use actually increases. For instance, energy efficiency improvements in automobiles have led to increased usage which in turn has increased the total amount of energy consumed by cars. Subsequently, end-of-pipe solutions (such as the catalytic converter) have been used reduce the impact of the waste gases. But the causes of the problem remains and new measures to reduce the pollution at the source (pollution prevention and precautionary principle) have to be taken.

There is potential to use process flow modelling to approach solutions which would bring opportunities to improve the manufacturing system in a holistic way and avoid local, suboptimal solutions. By following material, energy and waste (MEW) process flows with an integrated system view of the factory, it is possible to track down solutions to reduce environmental impact effectively while generating economic savings.

The work reported here aims to address: how can modelling MEW process flows form the foundation for more sustainable manufacturing facility design? This paper introduces a new approach to analyse manufacturing systems through the modelling of process flows in order to help manufacturers to identify potential improvements towards competitive sustainable manufacturing. Ultimately they could reach zero carbon manufacturing (ZCM) by having zero material resource degradation, zero net energy demand and zero waste across the system.

2. ZERO CARBON MANUFACTURING DEFINITION

In this study, physical resource inputs and outputs (material, energy and waste) are the main concern and are directly connected to the economic dimension. The use of the ‘sustainable manufacturing’ expression would entail a broad and holistic view including all three dimensions of sustainability or the “triple bottom line” [8] (economy, environment and society). Alternatively ‘zero carbon manufacturing’ leads to a narrower focus on CO_2 emissions and therefore on environmental impact and associated economic gains in the manufacturing system. It is widely recognised that carbon emissions are responsible for global warming, sea-level rise and other global changes [1], [11], [22], [16]. Carbon imbalance [13] is the most important environmental burden of modern society and thus the CO_2 emissions level is used as a proxy indicator [3] to reflect the efficiency of both energy and material flows within a system.

The use of ‘zero’ has implications regarding the accounting method and system boundary. For instance, ‘carbon-neutral energy system’ means that there is no direct CO_2 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_2 as it releases during its combustion. But taking a life cycle view of energy system, CO_2 emissions occur during manufacturing, commissioning, maintenance, and decommissioning. ‘Zero carbon’ emphasis the idea of CO_2 balance: the CO_2 emitted must be balanced over a given period of time.

Current techniques for carbon offsetting include Carbon Capture and Storage (CCS) or planting of trees, but these techniques are considered as parallel offsetting, whereas this study focuses on a more integrated way to achieve zero carbon.

Zero carbon concept in this study means:

- Zero material consumption: natural resource stock level is not decreasing, resource extraction rate does not exceed regeneration rate, closed-loop circulation of scarce materials such as non-renewables (see Zero waste below);

- Zero energy demand: energy use is minimised and recovery maximised (see Zero waste), systems produce at least as much energy as consumed on a yearly basis;

- Zero waste across the manufacturing system: elimination of toxic substances, minimisation of toxic substances and non-renewable resources in the system (for material as well as for energy), capture recoverable energy losses, recycle technical nutrients (substances which are useful in technosphere and sometimes persistent/harmful if released in ecosphere) and dispose safely of biological nutrients (innocuous substances which can be assimilated by the ecosphere).

Figure 2 shows how these three concepts and their associated tools interact.

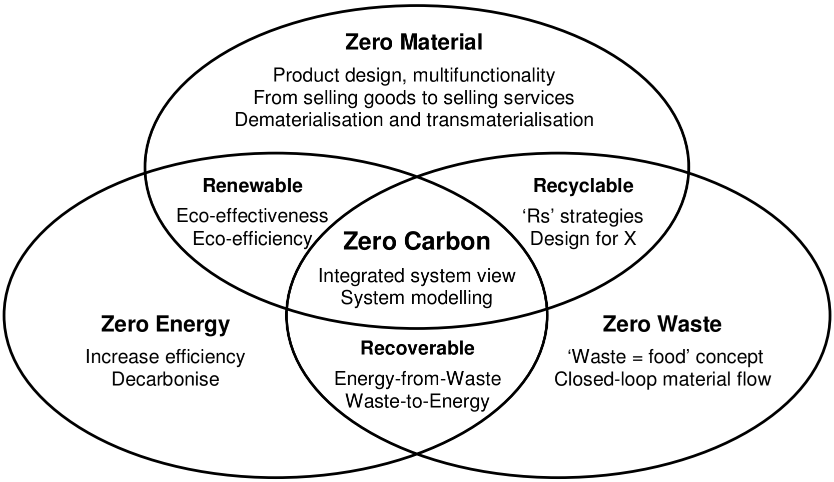

Figure 2: Zero Carbon Manufacturing concept definition

2.1. Material

In most manufacturing systems, zero use of resources in production is not achievable. Using exclusively recycled materials can be possible in some industries (shoe manufacture for instance) but in others, natural resource input is unavoidable. Sustainable resource use can be defined as the use of materials in ways that resources can be regenerated at least at the same rate as it is used in the system. This entails a complete elimination of non-renewable resource exploitation. With this idea in mind, the expression 'zero material consumption' (or zero material depleting use or sustainable material use) makes sense. Recirculation of materials within the technosphere using the '3Rs' (Reduce, Reuse, Recycle) strategies [7], [9] reduces the need for natural resource and contributes to reach the ultimate target of zero material consumption.

2.2. Energy

First, the energy used within the system must minimised. Then, the net energy demand must reach zero. Zero energy buildings are one example of energy balance or zero net energy demand: they produce at least as much energy as they consume. Through the use of renewable energy which does not have any direct emissions (except for biomass), the environmental impact of manufacturing activities can be reduced significantly. Some companies declare their manufacturing plant "carbon-neutral" by using 100% of energy from renewable sources either produced on-site or purchased from green energy suppliers [21].

2.3. Waste

Wastes can be divided in two categories: wastes which are not kept in technosphere (those ending up either in landfill or incineration) and recyclables which are fed back into the technosphere as inputs. Wastes can also be categorised into toxic and non-toxic. Zero waste is the idea of minimisation of toxic substances and creation of a closed-loop production system for those substances as well as for other technical nutrients. It aims at transforming the wastes into recyclables or making sure that wastes can safely decompose in landfill and become biological nutrients, or safely burn to produce energy (using CHP for instance) without emission of toxic gases. But does this mean all recyclables can be considered as truly non-waste? For instance, when materials are down-cycled into a lower quality product (open-loop recycling), it only reduces the natural resource input for the latter product but does not reduce the natural resource input or the recyclable waste output of the first product. One answer to this loss in material value would be to avoid the production of what William McDonough and Michael Braungart call the “monstrous hybrids” [15] (in which different materials are mixed together preventing proper recycling of the product).

3. ZERO CARBON MANUFACTURING APPROACH

Technologies provide a means of approaching Zero Carbon Manufacturing (ZCM) but which technologies should be used? How are these technologies linked together? A systems view of a manufacturing system and its surrounding ‘shed’ should be adopted. Using the MEW flows of an entire facility, the impact of a technology can be seen in context. This approach moves away from just transferring to clean energy and material sources for current demand to thinking in a more integrated way and focusing on improving their utilisation. The material and energy flows integrate the domains of the facility design and process engineering. The flows can be jointly studied by specialists from these two fields to jointly identify waste and opportunities to reduce waste by integrating flows rather than addressing the individual wastes in the respective fields.

3.1. Integrated System View of Manufacturing Facilities

Using a system view of the manufacturing facilities is a key element to approach solutions which would bring opportunities to improve the system as a whole and avoid local, suboptimal solutions. With knowledge of the potential flows, design methodologies can be developed to enable more sustainable manufacturing facility creation [2]. Through modelling of MEW process flows from a systemic viewpoint, potential interactions between processes can be identified in such way that material and energy losses can be recovered, “captured” and used in another process.

Beyond technologies and product design, few industries have considered their manufacturing system as an industrial metabolism [1] using natural systems as a model where material and energy are used not only in an efficient way, but also in an effective way [10]. By following process flows with a system view, it is possible to identify solutions to reduce environmental impact while generating economic savings.

By taking a system view, we acknowledge that everything affects everything else and therefore we need a tool which would help to anticipate those effects while allowing the identification of long-term consequences and root causes rather than the “easy way out” [12]. There is potential to use a process modelling approach to map MEW flows and analyse them for 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. But there is a lack of guidance and reference processes to assist manufacturing companies. The next section introduces generic MEW flow modelling and demonstrates how it can be applied.

3.2. Process Flow Modelling

Manufacturing processes cannot be zero carbon alone but when viewing such processes as part of a wider system it could be possible to achieve net carbon reduction. Thus it demands particular attention to potential process interactions rather than to isolated technologies or utilities, or else the approach will offer little advance over traditional tools (such as end-of-pipe solutions) to address problems rather than the source of the problems (such as pollution prevention and precautionary principle). A modelling approach could be used to analyse MEW flows and identify opportunities to recover outputs from some activities as inputs in others to reduce net consumption. It captures the complexity and the interactions within a system to enable better understanding of it.

The data collection must treat technologies as a 'black box'. The importance is what technologies are available and their inputs and outputs (see Figure 3) rather than their functional capabilities. Interestingly, literature typically focuses on the content of the black box or substitution of the technology rather than viewing manufacturing as a number of systems including the production processes and the production facility. Here the analysis is carried out with a process mindset to deliver an integrated process view of ZCM. From these process maps of a manufacturing enterprise, documenting MEW flows can be created.

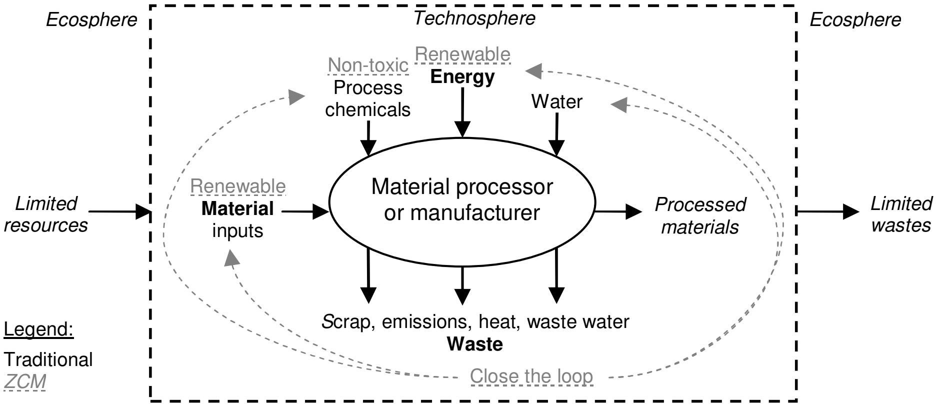

Figure 3: Generic diagram of a manufacturing process or manufacturing system

The techniques for mapping can range from simple static documentation of process sequences such as Material Flow Analysis (MFA) flowcharts, Integrated DEFinition for function modelling (IDEF) and Value Stream Mapping (VSM) to computer based discrete event simulation approaches that reflect the dynamic and stochastic nature of the flows.

MFA [6], [19] is a quantitative tool which accounts for physical flows and stocks of a given system including the hidden flows and captures the inputs and outputs based on the mass-balance principles (conservation of matter). The identification of wastes is a major advantage in MFA. The procedure makes use of life cycle analysis to ensure that all material flows are accounted for. As it aims at minimising the material use while increasing the value generated by the flow, it is associated with other practices such as zero waste and increased resource productivity. A major disadvantage of MFA is the requirements for high quality, detailed data, and it only considers physical flows.

The concept of IDEF [17] is able to conceptually map functions, which can be manufacturing processes or any other business activities, and multiple inputs and outputs in a system. In addition to physical flows, the controls (such as policies and legislation) and mechanisms (such as process automation) can be represented formally. Each function can itself be decomposed into a new diagram so that manufacturing processes are represented in greater detail and their associated inputs, outputs, controls and mechanisms are carried through to these lower levels.

VSM [5] is a well-established technique for manufacturing-specific static modelling of material and information flows, from customer demand through to suppliers. Importantly it is used to engage staff in improvement activities. Whilst it could be used for the process mapping being proposed here, the life cycle view of material waste is incomplete and supporting infrastructure and energy are ignored. However, the principle of engaging staff to catalyse ideas and innovation to move towards ZCM is a promising one.

The application of industrial ecology [11] aims at optimising the life cycle of virgin materials by taking a top down view of a system whereas the previously mentioned modelling techniques take a bottom up view. Life cycle approaches are being developed to move towards sustainable manufacturing [23], but these often focus on the life of the product rather than the manufacturing facility. Such approaches can provide a vision and framework to proceed but more detail is needed on the material and energy flows. Most approaches lack cognisance of embodied energy or the direct energy use and output and fail to recognise the wastes as valuable.

There is no single framework or process reference model that encompasses all the MEW flows from a manufacturing perspective. Generic flow modelling or process mapping are an approach for improving systems. They can act as a tool to support the development of a sustainable manufacturing system. They are helpful in highlighting the need to address the material and energy waste outputs of one activity and to prompt the search for links to the inputs of another activity, thus promoting the understanding of wider life cycles rather than functional operations.

The maps developed would be generic and contain significant detail. They would not be used directly but would be selectively instantiated to represent particular facilities and production systems. So for a given enterprise certain inputs and outputs would not be relevant and the detail of particular activities such as production would be added. Currently a library of individual production processes and their associated inputs, outputs, controls and mechanisms does not exist hence these must be developed as and when required. Ultimately, to be of most benefit, such flow modelling use needs to be guided by revised system design and improvement methodologies. Additionally work is needed on design methodologies that take a wider view of the industrial system life cycle.

4. CONCLUSIONS

With the objective of reducing the net consumption of material and energy in manufacturing, modelling of MEW process flows can help identifying potential combination of more efficient and cleaner technologies with existing facilities. A mapping technique to assist in modelling process flows in a manufacturing facility has been introduced in this paper. Individual technology solutions can be treated as ‘black boxes’ in order to primarily focus on their inputs and outputs, and on possible interactions where the outputs of some activities could be used as the inputs of others rather than treated as losses or wastes. The mapping approach is qualitative since this work cannot be carried out until the underlying system is understood hence the focus of this paper. The approach needs to be developed further to be quantitative to include aspects such as volume, duration, frequency, location, and quality of the flows. Simulation techniques are candidates for this analysis given their ability to represent both quantities and time.

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