1.2 Modelling and Tactics for Sustainable Manufacturing: an Improvement Methodology

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Abstract
Sustainable manufacturing practices demonstrated by companies are a key ingredient to increasing business performance and competitiveness. Whilst reported practices are good examples of what has been achieved, they are often company specific and difficult for others to reproduce since they provide few, if any, details on how improvements were achieved. Sustainable manufacturing strategies offer insight to the overall approach taken by companies but they can lack practical support for implementation. This paper examines the gap between strategic direction and practices to extract the mechanisms behind the practices and formulate sustainable manufacturing tactics (which provide information on how specific improvements can be implemented). The research is based on extensive collection and analysis of available case studies in published literature and interaction with industry. The combined use of resource flow (material, energy and waste) modelling and the tactics can support manufacturers in their journey towards sustainability by providing generic solutions on how to adapt their operations. An improvement methodology is developed by combining the manufacturing ecosystem model and tactics to guide manufacturers in a structured and systematic way to identify improvement opportunities. The paper explores the design challenge of developing such an improvement methodology to assist users in identifying which tactics might apply in their specific context.

Keywords:
Improvement methodology, Modelling, Sustainable manufacturing practices, Resource productivity, Tactic

1 Introduction
Manufacturing has traditionally been associated with undesirable environmental side effects [1] as manufacturers are responsible for the transformation of resource inputs into useful outputs (i.e. products with economic value) with limits on efficiency due to the laws of thermodynamics [2]. Over the last four decades, the environmental burden linked to industrial activities has become an increasingly important global issue [3–5] and a great challenge for society [6, 7].

Awareness about the impact of human activities on the global environment has promoted the implementation of environmental degradation prevention practices. These practices can be found under various labels and fields such as Industrial Ecology [8], Green Supply-Chain Management [9], Product Life-Cycle Management [10], Corporate Environmental Management [11], Design for Environment [12], Product-Service Systems [13], and many others [14, 15]. There are numerous factors playing a significant role in defining the requirements for a next-generation manufacturing paradigm, such as increased product and systems complexity, environmental concerns, lack of knowledge integration, technology advances in modelling and simulation techniques [16].

More recently, the concept of a Sustainable Manufacturing (SM) has been developed under various labels (e.g. Environmentally Conscious Manufacturing [17, 18] or Green Manufacturing [19]) as a sub-concept of Pollution Prevention (P2) [20]. The main objective of SM is to lower the environmental impact linked to manufacturing. Environmental activities have long been associated with a negative impact on business performance but this assumption has been proved wrong by many researchers [19, 21]. An illustration of both the economic and environmental benefits of SM is apparent in the cost savings due to energy reduction and waste minimisation. Research is rapidly developing and there are no established definitions or boundaries for studying sustainability performance of manufacturing systems. Throughout literature the flows of resources in the form of material, energy and associated wastes (MEW) reoccur [22]. The MEW flows must be interpreted in the widest forms to include not just primary material conversion but others inputs and wastes such as water, consumables and packaging.

SM can be thought of as a manufacturing strategy that integrates environmental and social considerations in addition to the technological and economic ones. The work presented in this paper focuses on the environmental aspects and emphasises on-site solutions rather than ‘product life cycle’ or ‘supply chain’. In particular the work focuses on generic tactics to improve the MEW flows within a manufacturing system and proposes an approach by which it can be examined. The tactics are created by extracting the mechanism of the SM practices and formulated so that they can be widely applied to multiple technologies and resources. It means that tactics must be generic to capture the principles of improvement, but sufficiently detailed to be adapted to the specificity of the system studied.

Using a manufacturing ecosystem model, modelling techniques can capture the MEW flows through a manufacturing system. It takes the user through the improvement methodology to identify improvement opportunities in resource productivity using the generic tactics to move towards sustainable manufacturing.
2 Research Methods

This research is part of a larger project developing a modelling and simulation tool [23, 24]. It aims to provide support for manufacturers to identify improvement opportunities in their MEW resource flow using generic tactics, an improvement methodology and modelling of MEW flows. It seeks to address the research questions “How can generic tactics support the identification of improvement opportunities in a systematic way?”

This research was conducted in two main phases: (1) theory building using Sustainable Manufacturing strategies and case study collection from the literature and (2) theory testing through the THERM project industrial partners.

In the first phase, case studies of sustainable practice in industry were collected from peer-reviewed and trade literature. Although the case collection showed there are many cases of sustainable manufacturing practices, there are few detailed reports on how to improve the sustainability performance as opposed to the benefits of implementing improvement measures [25]. The cases collected and analysed were classified to understand the breadth of practices in industry and understand how other manufacturers could implement similar improvements in their own factories. Practices were examined under the lens of the conceptual model of manufacturing ecosystem shown in Fig. 1.2.1 by focusing on the MEW flows linking the three system components (manufacturing operations, facilities and buildings). The generic tactics were then formulated to extract of mechanism of change and support the wide dissemination of these practices in the manufacturing industry [26]. A library of tactics was created to make them available in a format readily exploitable via the modelling tool being developed in THERM. The collection of practice is currently being extended to widen the range of best practices available in the database [25].

The second phase consisted of prototype applications of the manufacturing ecosystem model. The application includes testing of the library structure (classification based on how the tactics affect the MEW flows through the manufacturing system) and development of the associated improvement methodology for accessing tactics using process data.

The contribution to knowledge is the creation of a structured library of tactics that identifies the mechanism of improvements and allows generalisation of Sustainable Manufacturing practices. The contribution to practice is making tactics available to support manufacturers identifying improvement opportunities in a structured and systematic way.

3 Manufacturing System Modelling

The conceptual manufacturing ecosystem model [27] shown in Fig. 1.2.1 is based on the Industrial Ecology model type II [28]: the system’s input (overall resource intake) and output (waste and pollutant emissions, product output being kept in the technosphere) are limited, and the resource flow within the system has a certain degree of cyclicity. It means that the sum of all flows within the system is higher than the total inputs and outputs to the system, therefore reducing the dependency of the system on external resources and sinks and its environmental impact.

The model shows the three main components of the manufacturing system: manufacturing operations, supporting facilities and surrounding buildings. All three components are linked by resource (material, energy and waste) flows. Various strategies (or themes or principles) for sustainable manufacturing were collected from literature [29–31] and can be summarised as follow:

1. Avoid resource usage and improve conversion efficiency: use and waste less by dramatically increasing the productivity of natural resources (material and energy);
2. Close the loop of resource flow: shift to biologically inspired production models such as reduction of unwanted outputs and conversion of outputs to inputs (including waste energy): recycling and all its variants;
3. Change supply or replace technology: reinvest in natural capital through substitution of input materials: non-toxic for toxic, renewable for non-renewable;
4. Shift paradigm: move to solution-based business models including changed structures of ownership and production: product service systems, supply chain structure.