Chapter 1

The Changing Landscape of Energy Management in Manufacturing

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Additional information is available at the end of the chapter

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Abstract

The production and use of energy accounts for around 60% of global greenhouse gas (GHG) emissions, providing an intrinsic link between cause and effect. Considering that the manufacturing industry is responsible for roughly one-third of the global energy demand enforces the need to ensure that the manufacturing sector continually strives to reduce its reliance on energy and thus minimise GHG released into the atmosphere. Consequently, efficient management of energy consumption is of paramount importance for modern manufacturing businesses due to well-documented negative impacts regarding energy generation from fossil fuels and rapidly rising worldwide energy costs. This has resulted in a proliferation of research in this area which has considered improvements in energy consuming activities at the enterprise, facility, cell, machine and turret levels. However, there is now a need to go beyond incremental energy efficiency improvements and take more radical approaches to reduce energy consumption. It is argued that the largest energy reduction improvements can be achieved through better design of production systems or by adopting new business strategies that reduce the reliance of manufacturing businesses on resource consumption. This chapter initially provides a review of research in energy management (EM) at various manufacturing focus levels. The inappropriateness of current methods to cater for transformative and radical energy reduction approaches is discussed. In particular, limitations are found at the business strategy level since no technique exists to consider the input of these high level decisions on energy consumption. The main part of the chapter identifies areas of further opportunity in energy management research, and describes a method to facilitate further reductions in energy use and GHG production in manufacturing at the business strategy level.

Keywords: Energy management, Greenhouse gases, business strategy, manufacturing, sustainability

1. Introduction

There are two facts about the future of energy that we know: we will not be able to generate the same quantities from easily accessible fossil-based sources as we currently do, and in the short term this shortfall in energy supply will not be met by 'renewable' sources based on current projections of investment and development [1]. In addition, energy consumption is currently increasing (see Figure 1) and is expected to increase by 22% by 2020 compared to 2011 [2], due partly to increases in demand from China and India [3]. These factors will create what has been termed the 'energy gap' [4]: the difference between demand for energy and the ability to supply this demand, although it should be noted that demand is influenced by supply. The precise magnitude of this energy gap is difficult to predict but it will have a severe influence on the way energy is consumed in the foreseeable future.

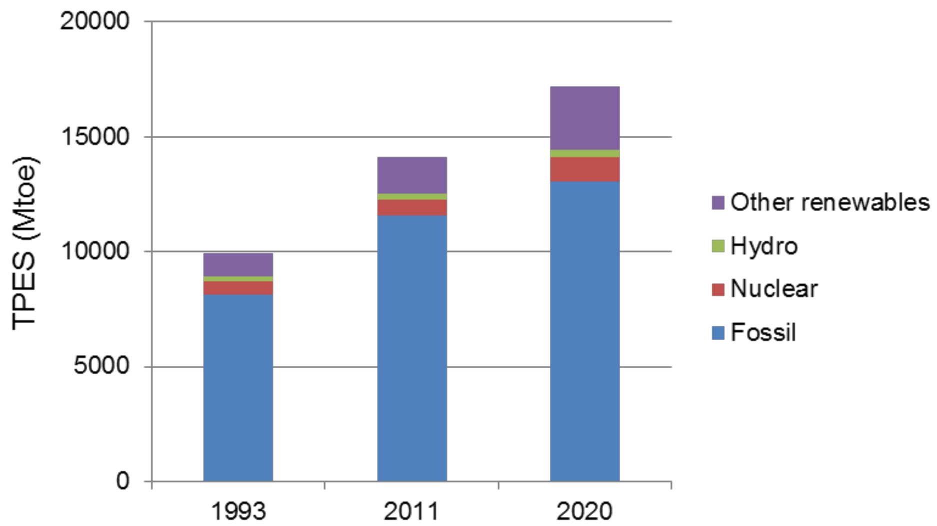

Figure 1. Total primary energy supply of resource by 1993, 2011 and 2020 (data from [2])

The management of energy consumption within the manufacturing sector is particularly important since it is one of the largest energy consuming sectors, directly and indirectly responsible for one-third of global energy use and carbon emissions [5]. This high level of manufacturing related energy consumption is particularly true in developed and developing countries [6]. Energy security is therefore vital for the future of the manufacturing industry and provides a significant incentive to reduce consumption levels. Other incentives also exist in the form of rising energy costs, national and international legislation and consumer demand for greener products. This need has not gone unnoticed and a wide range of approaches have been implemented by companies to reduce reliance on non-renewable (fossil-based) energy sources by improving management practices of energy consuming activities.

These EM techniques have been, in general, quite successful for specific applications but are limited in their scope and so can only ever have a predetermined impact on an enterprise's energy performance. Historically research and the resulting EM techniques have focused on current manufacturing operations and management practices and have therefore tackled problems that can be solved by existing industrial companies. However, modern manufacturing businesses are under ever-increasing pressures to deliver innovative solutions for highly complex tasks for adaptability, economic performance, maintainability, reliability, and scalability. The "Factory of the Future" [7] has to be adaptable not only to the needs of the market but also to the growing requirements for economic and ecological efficiency. Furthermore, such factories will have to take into consideration increased levels of social responsibility and, in particular, environmental sustainability. Based on these challenges, the need for development and validation of new industrial models and strategies is relevant for industrial transformation. These competitive sustainable manufacturing models and strategies will have to aim at achieving long-term economic sustainability through an increase in added value and improved production capability, responsiveness and quality as well as environmental sustainability through the decrease in the consumption of raw materials, water and energy.

The shape of manufacturing is therefore changing as life cycle approaches become more important for impact assessment and the use of ecological data to influence process planning becomes necessary to meet the environmental performance characteristics demanded by government, industry and consumers. In addition new business-strategies[1] are being explored [8–9], with a wide spectrum of product service systems, remanufacturing and product upgradeability, all likely standard models for the future of sustainable manufacturing industries.

This chapter, which identifies the existing trends in EM research for the manufacturing sector and develops new EM regimes that are important for continued advances in energy rationalisation, is divided into three main sections:

- A brief review and analysis of existing EM techniques for manufacturing with a short discussion on developing new EM techniques for evolving manufacturing approaches;
- A more detailed discussion regarding the need for the consideration of business strategies within EM for manufacturing, with the development of a procedure to facilitate this consideration; and finally,
- A case study to demonstrate the applicability of the developed EM procedure for the business strategy manufacturing level.

2. Review of Existing EM Techniques

Manufacturing enterprises and facilities can be highly complex, where monitoring energy consumption and associated GHG production can be cumbersome and expensive. Using a

1 In this work, business strategy defines the approach in which a manufacturer takes to fulfil the need or want of the customer. The manufacturer will supply a solution through either the provision of a product or service (which uses a product) and can, therefore, be a short-term or long-term interaction with the customer. Similarly, the business strategy also defines where and when and how often manufacturing processes are undertaken. In short, business strategy defines the model by which a company seeks to generate profit from its customers, but which is also linked to its suppliers and external governing bodies.

well-structured framework can help industrialists identify where to focus their efforts to achieve maximum energy savings. One structured approach to analysing a manufacturing system is to decompose the system hierarchically. A variation of the 'shop floor production model' as developed by the International Organisation for Standardization (ISO) can be used to categorise research conducted on various levels. The adapted model has five levels, ranging from a high level to a specific scope. The levels and the energy considerations for each are summarised as follows:

1. Enterprise level – supply chain of materials or components, network of production sites, inventory hubs, sales and distribution centres, R&D and the integration of various plants.

2. Facility level – building envelope, heating, ventilation and air-conditioning (HVAC), infrastructure of the facility and site energy generation.

3. Production/machine cell level – planning, production engineering and management, supply of material resources and maintenance.

4. Machine level – operation and control of equipment, lighting, cooling, work done on material and communication systems.

5. Turret or tool-chip level – actual transformation of material.

Further, Vijayaraghavan and Dornfeld [10] also suggested that at each level of analysis, there is a corresponding temporal scale of decision making that ranges from several days at the enterprise level to micro-seconds at the tool-chip level. The range of variation in the analysis and temporal scales along with the types of decisions that are made at each level is shown in Figure 2. It is considered by the authors that although the temporal timescales suggested by Vijayaraghavan and Dornfeld [10] are suitable for rapid, high-volume manufacturing processes (e.g., low-tech electronics), for products that are highly complex (e.g., jet engines) or for products that have very long product runs (e.g., cars), these decision timescales need to be extended. This is particularly the case when a decision is based on the use of sufficient historical data (which needs to be collected and interpreted). The current research considers temporal timescales between minutes (real-time) and years (strategic).

The following sections use the structure described above to briefly review some of the techniques for EM and minimisation published in recent academic literature. The review is not intended to be comprehensive (see [11] for a review with a wider scope) but is intended to show the shape of research in this field with respect to decision time scales for each manufacturing level. As will be shown, existing research (in EM) falls into the manufacturing level-timescale relationship described by Vijayaraghavan and Dornfeld [10]. This research is concerned with identifying the opportunities and needs for EM techniques that lie outside of this existing envelope. These new areas of energy consideration in manufacturing are shown in Figure 3.

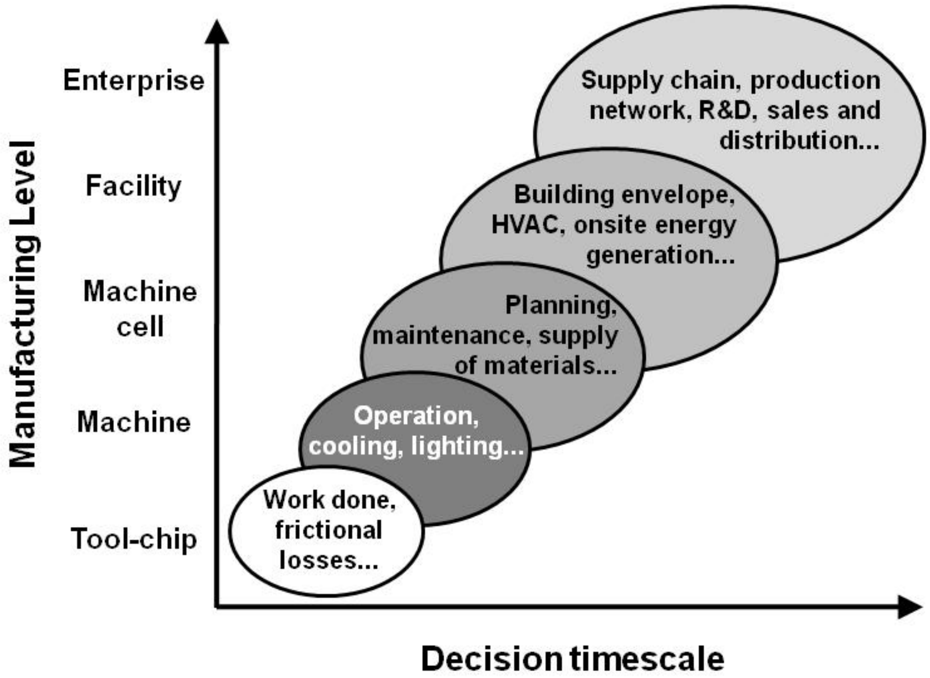

Figure 2. Energy considerations at different manufacturing levels. Adapted from [10].

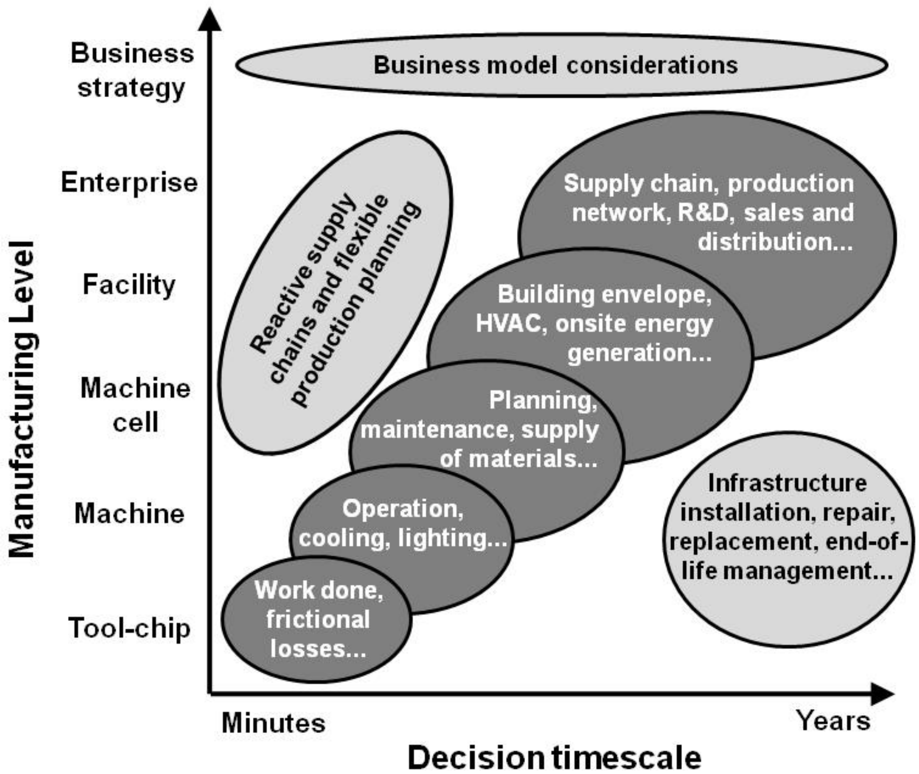

Figure 3. Energy considerations in manufacturing. Existing research predominantly in dark grey areas. New areas described in this research shown in light grey.

2.1. Energy Research on an Enterprise Level

Manufacturing enterprises extend beyond the walls of a factory that just produces goods; they encompass a range of activities from supply chain of materials or components to manufacturing processes and the logistics of the finished product. This involves a network of production sites, suppliers, inventory hubs as well as sales and distribution centres.

Various studies have reported techniques for EM at the enterprise level. Concentrating on logistics Kara and Manmek [12] found that the embodied energy of products could be reduced by selecting local suppliers and avoiding road transport for high quantities of raw materials over long distances. Their model focused on energy, materials and emissions, and waste with considerations for how each of these are used or produced within lengthy supply chains. Supplier location was shown to be a significant factor that can increase or reduce the embodied energy of the raw materials. A similar study [13] used Google Maps to carefully plan and optimise the embodied energy of transportation at the enterprise level. Both approaches require detailed data regarding transport modes and routes and, in the event of instigating changes, may require extensive replanning of multiple cross-linked supply chains. In addition, Kara et al. [14] detail a methodology for assessing the impact of global manufacturing on the embodied energy of products. They studied six different products manufactured from various raw materials in a global manufacturing network and found that product, material and key supply chain parameters played a crucial role.

Other research on the enterprise level has identified that energy improvements can be obtained by changing manufacturing models (e.g., Seliger et al. [15] showed that a phone that is remanufactured consumes less energy than a phone that has been sent to a land fill, over the production, use and end-of-life phases). This is because the remanufacturing pathway, despite requiring energy input into the reverse logistics, avoids repeating manufacturing steps with characteristically high energy consumption and environmental emissions.

The globalisation of businesses has led to long and multi-tiered supply chains, making the introduction of improvements across the entire enterprises complex and difficult. This has been reflected in the number of studies that have been carried out at the enterprise level with most publications focussing on case studies and observed trends rather than on new methodologies [11]. In general, the higher costs, coordination effort and complexity and communication difficulties of implementing sustainable supply chains has led companies to focus on internal activities that present far more achievable environmental (and financial) gains over shorter time periods.

2.2. Energy Research on a Facility Level

Research on the facility level primarily focuses on modelling and reducing the energy consumed by infrastructure and other high level services such as ventilation, lighting, heating and cooling. On-site energy generation is also taken into account.

A review of potential energy savings of a typical manufacturing facility has been performed [16] and focused on high-level redesign strategies. It was concerned with the potential energy saving that can be achieved through optimised building shape and form, improved building envelopes, improved efficiencies of individual energy using devices, alternative energy using systems in buildings, and through enlightened occupant behaviour and operation of building systems. In addition, a method for measuring plant-wide industrial energy savings that takes into account changing weather and production between the pre- and post-retrofit periods has been presented [17].

As a barrier to EM at the facility level, it has been highlighted there is a distinct lack of manufacturing energy performance indicators (EPIs), and this has led to difficulties of modelling 'plant level' energy consumption [18]. Benchmarking energy is essential for EM program development, yet it has been noted that most industries have not, or at least have not been able to, benchmark energy use across their plants. Combining the American Energy Star performance rating system with EPIs, it has been possible to quantify the average energy consumed for the manufacture of best practice vehicles [18]. On a more generic level, the development of energy performance benchmarks and building energy ratings for non-domestic buildings have been reported [19]. They outlined a methodology to develop energy benchmarks and rating systems starting from the very first step of data collection from the building stock.

Finally, on the facility level an economic comparison of three cogeneration steam systems for a wood pulping mill was carried out [20], finding that economic and environmental optimisation could not be achieved simultaneously.

2.3. Energy Research at the Machine Cell Level

At this level, research focuses on planning, production engineering and management, supply of material resources, transport waste material processing and maintenance. Energy flows are closely related to the running of these activities that may be affected by production plans, scheduling times and parameters.

Much of the research reported on the production level involves process planning and process routing for improved energy performance, although most research focuses on costs and cycle times. There is a lack of tools for optimising process flows based on sustainable development objectives (environmental), and those that have been proposed have few practical results [21]. In an attempt to bridge this gap, Tan et al. [21] combined manufacturing process planning and environmental impact assessments using a checklist analysis. They proposed an optimal decision making method for new components that include energy consumption as part of the sustainable development evaluation.

In addition, He et al. [22] have developed green manufacturing process planning and support systems where the raw materials, secondary materials and energy consumption, and other environmental impacts of process planning were optimised. This was supported with databases and model repositories. Integration of the optimisation of energy consumption of processes as part of the process selection algorithm in a process planning program is also possible as and has been demonstrated [23].

Information is critical on a production level: Chiotellis et al. [24], Müller and Löffler [25] and Herrmann et al. [26] have all proposed various information formats to aggregate energy values for decision making on a production level. These groups specifically noted a current lack of monitoring of energy flows within factories. In addition to the lack of monitoring systems, the amount of information required can be very complex and requires a robust framework to deal with information on all levels. They suggest that having online monitoring of the energy consumption within a factory not only provides greater energy transparency, but also provides a stream of useful information to be used for maintenance repair and overhaul. To facilitate this, they have introduced the concept of EnergyBlocks, which can help planners to evaluate the energy consumption profile of various alternatives and to deduce optimal system configuration. However, data volumes increase (almost exponentially) as you move down the manufacturing levels, and it is therefore important to set the correct resolution through appropriate hardware and software systems.

Muller and Loffler's [25] approach to the same problem provides guidance on energy-related decision making during the planning procedure, from the product definition to energy monitoring of the implemented plant. The availability of energy-related data in industry during the planning process is still very rare, and so the main challenge is the development of energy data standards for life cycle engineering (LCE) tools. They have suggested the development of energy performance ratios to influence more detailed standards and instruments such as the dynamic simulation of energy demands.

The correlation of energy usage with operations being performed in the manufacturing system through event stream processing techniques has been successfully implemented [10]. The framework temporally analyses the energy consumption and operational data of machine tools and other manufacturing equipment to enable decision making to improve the environmental performance of the machine tools.

2.4. Energy Research Associated with Production Machines and Equipment

Research associated with the machine level has been concentrated in two subcategories: the energy consumption of the machine for the 'work done' processes and the energy requirement of the machine for auxiliary processes (e.g., cooling and control).

Cooperative Effort on Modelling Process Emissions in Manufacturing (CO2PE!) is an international initiative [27] to cluster forces in different continents, involving machine builders as well as academics, to analyse existing and emerging manufacturing processes for their ecological impact in terms of direct and indirect emissions. Substantial research has been targeted to document, analyse and reduce process emissions for a wide range of available and emerging manufacturing processes [24, 28–31].

In the life cycle phases of product manufacturing, the focus of resource efficiency moves from the material applied per unit to resources used in the various production phases, for example, cooling lubricants, compressed air or hydraulic oil and on the energy requirements of the production processes [24]. Process relevant information is based on equipment energy consumption curves. Each curve is specific to a production equipment item and enables an accurate determination of the energy consumption of the item over the production time.

Similarly, Overcash et al. [32] produced an engineering rule-of-practice-based analysis of separate unit processes used in manufacturing. The information is collated in the form of a unit process life cycle inventory, which then helps to evaluate the manufactured products through the quantification of various parameters, including input materials, energy requirements, material losses and machine variables.

In the context of an integrated consideration of economic and ecological impact, energy profiles are an important basis for deriving optimisations to improve sustainability in manufacturing [33]. On the process level, these profiles permit the identification of substantial energy drivers in machines. In addition, the process-specific energy assessment has taken a step further to develop generalised 'equipment-level' energy models, using average energy intensities of different manufacturing processes to evaluate the efficiency of processing lines [34]. They concluded that modern processes enable smaller dimensions and scales to be produced with larger specific electrical energy requirements. They indicated that energy requirements depend on the production rate and are consequently not constant as assumed by Life Cycle Assessment software packages like Simapro or Umberto.

Dahmus and Gutowski [35] tracked energy flows when characterising the environmental impact of machining, making a distinction between the energy required for chip formation and operating the manufacturing equipment (Figure 4). In their studies, they showed that machine tools with increasing levels of automation reveal higher basic energy consumptions that result from the amount of additional integrated machine components.

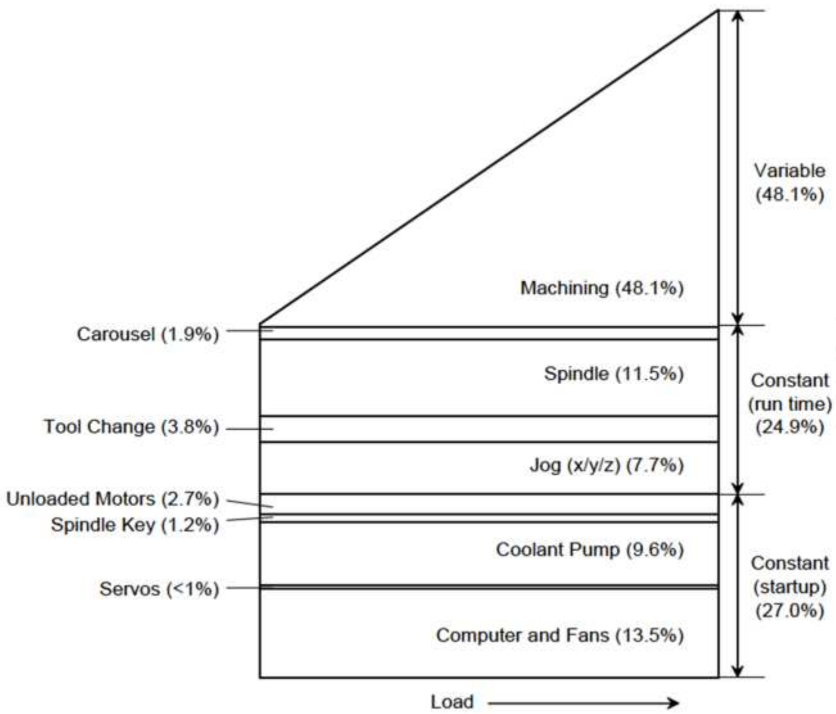

Figure 4. Machining energy use breakdown for a 1988 Cincinnati Milacron automated milling machine with a 6.0 kW spindle motor [35].

More specifically, a study on the energy consumption of cutting found that high speed cutting required less energy per unit manufactured compared to the conventional cutting speed [36]. They also found that the installation of kinetic energy recovery systems (KERS) can reduce average power consumption by up to 25% depending on workpiece geometry and machining time. As the energy efficiency of the system is highly part specific, a KERS should be custom defined. A framework has also been developed [37] for the recovery of waste heat energy from manufacturing processes.

Along the same theme, the improvement potential in two types of manufacturing equipment for discrete part production has been discussed [29]. Power requirements for activities in a machine tool was investigated and classified into productive and non-productive periods.

In contrast, however, Fleschutz et al. [38] conducted an energy simulation on 12 similar industrial robots within a workstation and found that the assigned operations strongly influenced the energy consumption of the respective robot. Even though the operating hours are the same for the robots, those that had more kinematic movements and little idle time resulted in energy consumptions that were double the other robots.

Process conditions and energy consumption are not normally static but depend directly on the specific conditions of the process and/or the production setting. The initiation of energy labels for production machines indicating the amount of electrical energy consumed for various production processes has been proposed [30]. Such information can be estimated by summarizing the electrical energy consumptions of single machine components (pumps and engines) or by using energy profiles to reveal the holistic energy absorption that is needed by machine tools.

There are, however, significant challenges in obtaining sufficient energy consumption data. It has been proposed that in the future, both the manufacturer of equipment and the operator should use consistent parameters to describe the energy performance of manufacturing systems and that equipment should have standardised metering ports [39].

2.5. Energy Research on the Turret Level (Theoretical Process Energy)

The lowest and most focused manufacturing level is the turret level, which represents the actual material transformation process itself. Energy assessment and management at this level involves knowledge of the interactions of the mechanical and chemical processes in order to establish theoretical energy consumption values of the process.

The research and application of improvement in energy efficiency at the turret level is highly process specific and therefore less appropriate to general application. As a reflection of this, less research has been published at this level. Most research is evaluative with little scope provided for developing models. Consequently, only a few examples reviewed here are used in further analysis in this chapter.

At this focus level, it has been shown that in machining, the ideal process energy is independent of operating parameters such as tool speed, feed and depth of cut [40]. Instead the machining energy is dependent on setup parameters, such as choice of cutting fluid, tool rake angle and

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part design parameters (material selection and the volume of material removed). Draganescu et al. [41] conducted experiments to model machine tool efficiency so that the specific consumed energy could be determined for establishing cutting parameters and the consumed energy necessary for removing a certain quantity of chips. Amongst many examples of theoretical mathematical modelling of machine processes, Draganescu et al. [41] and Kalpakjian and Schmid [42] have looked at the specific energy consumption for milling, and Ghosh et al. [43] have modelled the specific energy requirement of deep grinding.

Other studies of theoretical energy consumption of other manufacturing process can be found in [42] who give detailed explanations and descriptions of the energy required for cutting, forming and deformation. A detailed analysis on the specific cutting energy for bandsawing different work piece materials has been carried out [44]. The minimal energy required for turning and the optimal conditions for machining a product has been studied [45] and finally Kuzman and Peklenik [46] have done an energy evaluation of cold forming processes.

3. An Overview of the Current Scope of EM

There are clearly a large number of EM techniques that manufacturers can implement in order to reduce their energy consumption and their generation of GHGs. These techniques focus on many different aspects, and it can be confusing for manufacturers to decide which approaches are best for their particular setup. One way of categorising these different EM techniques is to define the temporal decision timescale. Within manufacturing, EM decisions can be made on one of four timescales: real-time (minutes-hours), operational (days-weeks), tactical (months) and strategic (years), with EM techniques at these levels being implemented by different groups of people who operate at different management levels.

Positioning the EM techniques reviewed in this chapter into a research map (Figure 5) that has manufacturing level and decision timescale as its axes reveals almost intuitive results. The more focused (lower manufacturing level) an EM technique, the shorter the timescale on which decisions can be made: adjusting machine setup parameters (turret level) can be done by one person in a few minutes, whereas reconfiguring a supply chain (enterprise level) will take a team of people months or even years. In the research map, this correlation seems linear, but since the x-axis is not continuous and the y-axis is not quantitatively scaled, a strict correlation is undefinable and inappropriate. Nonetheless, there are clear areas of the map that are not occupied by any of the reviewed EM techniques, and it is therefore suggested that there is a need for research to be undertaken to address these areas.

There are two areas of research in the current map (Figure 5) that would benefit from a growth research: lifecycle process system planning and eco-intelligent manufacturing and agile supply chains. A further area of research, not currently represented on the above map, is required to look at the impact on energy consumption of existing and future business strategies. These three research opportunities are discussed in the following sections, with EM at the business strategy level given a more in-depth consideration due to the importance of its potential for limiting GHG production (energy consumption) in order to meet a specific customer need.

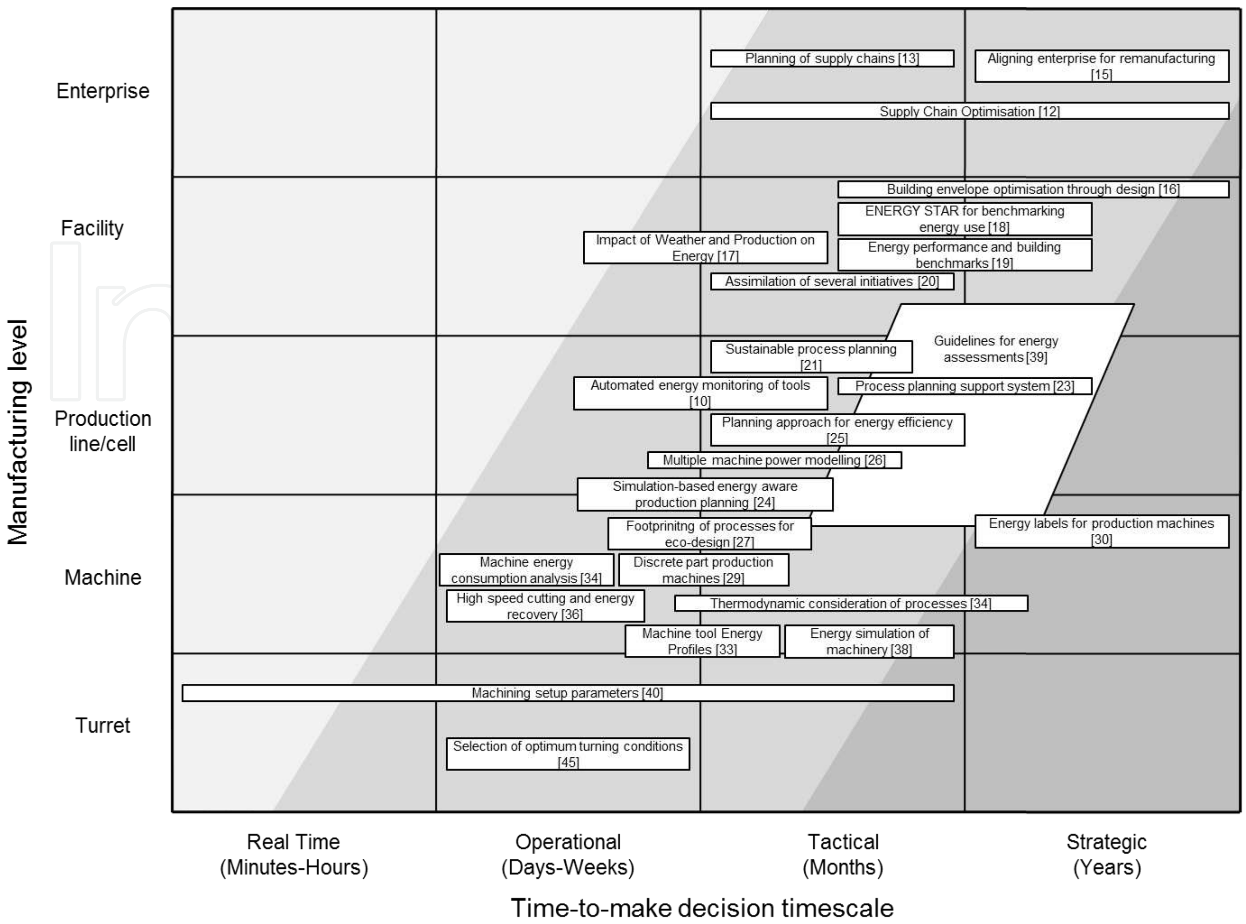

Figure 5. Research map showing the relation between manufacturing level and associated decision timescale. The mid-grey region is heavily populated, whereas EM techniques at for short-term facility and enterprise energy consumption and long-term process level energy consumption are largely undeveloped.

3.1. Lifecycle Process System Planning

Recently, as with products, manufacturers are beginning to take a life cycle view of not just their factories, but also the processes within the factories [47]. Primarily for economic reasons but also from an environmental point of view they are beginning to consider how best to ensure their machinery is maintainable and upgradeable, and what will happen to it at its end of life. Such a task can be highly complex since it is difficult to predict the requirement of future or long-term process capabilities, process utilisation levels and also production floor layouts. Life cycle process planning is, therefore, heavily dependent on a company's ability to roadmap the sector it operates in. However from an environmental perspective, it is highly important to be able to consider the resource intensity of processes throughout their lifetime. A host of life cycle process planning tools are therefore required to assist manufacturers in managing their long-term process requirements. For this, they require the development of an assessment framework and decision support tool to understand the life cycle impact of individual processes and process chains so that strategic decisions can be made about the purchase or upgrade of machinery to ensure minimal environmental and economic impact.

Such a suite of tools requires a consideration of energy consumption to ensure the processes are able to integrate with the long-term energy supply strategy of a particular facility. Life cycle process EM should consider flexible, reconfigurable process chains, peripheral energy requirements (cooling, transport systems, etc) and factory layout to ensure the most appropriate planning is carried out. EM tools developed in this area will need to provide manufacturers with clear strategies for the minimisation of process energy consumption over periods of many years. Such considerations will be key to the development of eco-efficient factories for sustainable industrial systems.

3.2. Eco-Intelligent Manufacturing and Agile Supply Chains

At the short end of the temporal decision timescale on the research map, there currently exists another area where no or very few EM techniques exist. In this region, which covers manufacturing levels between cell and enterprise, manufacturers are beginning to consider new short-term influences on their production and operations processes to improve economic and environmental performance. As part of a holistic approach, they require techniques to help them manage their energy consumption at this timescale.

At the production cell and factory levels, real-time consideration is required to be sensitive to energy availability, which may come from several sources (almost certainly involving traditional fossil-based energy) and which for any renewable component may vary in supply. In such circumstances, it is necessary to be able to rapidly influence production scheduling to ensure that energy intensive processes are carried out at periods of higher renewable energy availability to maximise the environmental benefit from this type of energy. Smart metering and smart energy grids are required to influence this eco-intelligent manufacturing. In fact, a new production planning regime, 'environmental resource planning', is required to not just take into account the immediate availability of energy supply mix, but a full range of eco-indicators, including emissions, water consumption, idle time of processes, and staff availability.

There is also a need for industry to be able to consider and manage energy at the enterprise level, but on the short real-time and operational timescales. Supply chains have historically been set up to optimise for time and cost to give manufacturers the best possible competitive advantage. However, this approach has led to disadvantages in fluctuating markets and increasingly, manufacturers are seeking to remain resilient by creating flexible reactive supply chains. The Triple-A Supply Chain described by Lee [48] promotes the need for agile supply chain arrangements that are able to respond to short-term changes in supply, allowing rapidly changing consumer demands or unforeseen disruptive events to be more easily worked around. The energy implications in an agile supply chain need to be managed even if it might not be a primary consideration. It is important for companies to be able to account for the resources that are required for their products from a life cycle approach, which includes being able to optimise the supply chain. Methods for systematically reacting to supply and demand problems are being developed [48] and incorporated into everyday business practices. EM techniques that are able to consider and influence these short-term reactive changes to supply chain operation will be essential for improving and maintaining environmental performance in the future manufacturing industry.

3.3. Energy Management at the Business Strategy Level

The preceding reviewed and hypothesised EM techniques for manufacturing are suitable for current make-sell business models that are optimised for economic benefit. Since profit is generated from the sale of products, successful manufacturing businesses have historically been those that produce and sell more than their competitors: a culture that has led to a disregard for resource consumption and pollution levels. This practice is now changing as businesses and consumers become more aware of, and active in achieving long-term sustainability. Manufacturers are investigating and implementing radical new strategies to remain commercially competitive whilst reducing resource consumption. It is therefore proposed here that new EM techniques will be required to support these new manufacturing business strategies.

The field of manufacturing has seen many improvements in sustainability performance over the last few decades. Strategies to reduce waste, lower emissions, improve energy efficiency, and so on have been implemented across the board but such activities have largely made improvements for individual processes only. In the long term, industrial sustainability will not be achieved simply by the development of new technologies or the utilisation of iterative improvements of current production processes. Accordingly, the appropriateness of existing business models are being challenged [49–51] for a future of industrial sustainability. The configuration of the industrial system will evolve dramatically, introducing new concepts such as cradle-to-cradle [52], slow manufacturing, local manufacturing [53], product service systems [9], and product compatibility and upgradeability [54].

An additional manufacturing level is required to consider implications of cost, energy and other resource consumption for these new business strategies [55]. Since for manufacturers the primary consideration in choosing a business strategy will always come down to cost and profit, it is unlikely that any manufacturing activities will be fully optimised for energy efficiency. However, by being able to understand how energy can be considered, measured and managed at this high level, significant energy improvements could still be made. Through the development of new EM techniques, it is important to be able to consider the life cycle manufacturing energy consumption of products as well as the life cycle energy consumption of manufacturing processes and facilities used to produce these products. Figure 6 shows an updated and simplified version of the EM technique research map, which includes the proposed business strategy manufacturing level. Preliminary guidelines for the consideration of energy consumption factors at this business strategy level are discussed by comparing two different business strategies for furniture.

Two distinct and simple business strategies for manufacturing household furniture may be described as the provision of either low-cost, short lifespan, or expensive, long lifespan products. The decision on which strategy to take is made at the conception stage of the business and may depend upon existing supply chain links, market opportunities or available workforce skill set for example. It is unlikely that such a strategic decision would ever be made

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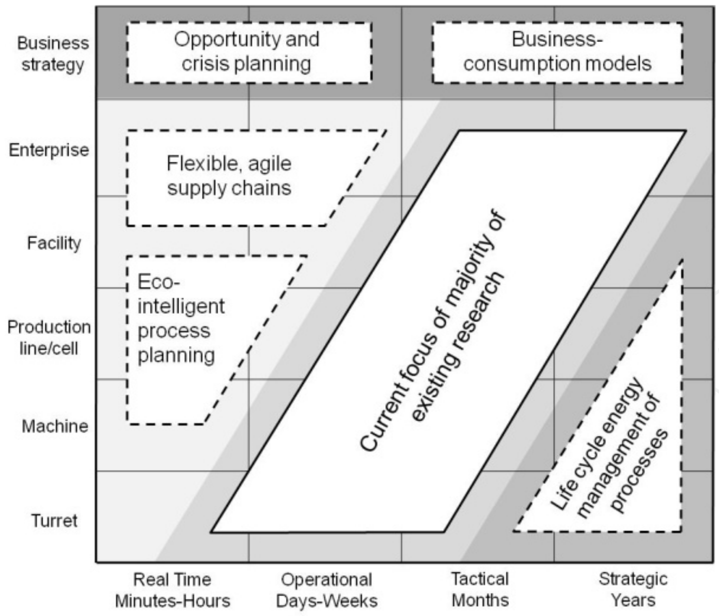

Figure 6. Manufacturing level-decision timescale map showing positioning of required focus for EM to contribute towards industrial sustainability.

purely on the merits of energy consumption levels, but the decision itself has a significant implication on energy use. Table 1 shows some differences between the individual approaches for the manufacture of the furniture. EM techniques are required to assess the different impacts of the two strategies to enable effective EM decisions to be made.

For the short life products, the manufacturer requires a rapid production throughput, and low cost, lightweight materials are likely to be used, which can be quickly manufactured. Because of the highly competitive low selling price of the short-life goods, profit margins are low and therefore there is an economic need to have high volumes of production ensuring that the market remains in constant need of new furniture. For this type of production, low manufacturing costs are essential and so rapid, highly efficient and centralised manufacture is of key importance, and therefore, the embedded energy [56] per product is likely to be relatively low.

Short-life furniture	Long-life furniture
· Energy efficient process	· High quality processes
· Rapid production	· Quality-driven production
· Automated production	· Semi-automated production
· High throughput	· Low throughput
· Low profit margins	· High profit margins

Table 1. A comparison of different manufacturing considerations for short- and long-life furniture.

Conversely, for long life products, materials and manufacturing processes are quality driven with less regard for cost, which will be easily recuperated by high profit margin sale prices. As the products are intended to last a long time, the manufacturer is keen on brand awareness and will ensure their products are of the highest quality. Slower, more energy intensive procedures are likely to be used with additional finishing, inspection and testing processes. Distributed manufacture from small facilities is likely to be preferred to be adaptable to regional market requirements. For this type of product, the embedded energy per unit is likely to be relatively high.

Since the object of manufacturing is to provide a functional unit for a particular market need, a key indicator is the length of time a product fulfils a need. The longer the life of the product with respect to energy consumed, the more energy efficient the manufacturing of the product. This energy per product year, E_{PY}, can be expressed in simple terms as E_{PY} = energy required for manufacture/product lifetime.

Applying this measure to the present example we can consider that the total energy consumption required for an item of furniture is the summation of embedded product energy, E_E, and amortised (i.e., per product) energy from the lifetime of the production processes (i.e., the energy required to produce, maintain and repair the process machinery), E_P, and the amortised energy from the facility, E_F, then the energy attributed to each year of the product's life can be expressed as $E_{PY}= (E_E+ E_P+ E_F)/L_P$, where L_P is the average anticipated product life in years. Note that if the producer has responsibility for the disposal of the product at its end of life, the energy requirement for this also needs to be considered in the above equation. Other considerations at this business strategy level might include the possibility of remanufacture (lowering future E_E), availability of renewable energy (lowering the impact of E_E), production at low energy demand periods and maintenance contracts.

The product lifetime is of utmost importance in the case where significantly different lifetimes of products are being considered. In this example of furniture, it is not unreasonable to assume an order of magnitude difference in lifespan. Assuming there is no significant difference between the production energy, the business strategy that manufactures longer life furniture will be preferable.

Regardless of which business strategy is used, the process of considering the energy consumption factors throughout the life cycle of the products can be used to influence the selection of manufacturing processes, facilities, facility operation times, and so on. Clearly, as with EM techniques at lower manufacturing levels, approaches at the business strategy level require availability of suitably reliable or indicative data, or appropriate assumptions. In addition because of the complexity of different business models, such high level EM may require significant input from techniques focussing at lower levels of EM (e.g., HVAC control to reduce E_E) to yield the best results.

There is a need for the development of new EM techniques at the business strategy level that assist manufacturers not only in deciding which production models are least energy intensive, but also in minimising energy consumption at the highest level with an integrated approach. Importantly, such EM techniques need data for the specific stages in a product's life cycle for which the manufacturer is responsible. By using energy per product year as the unit of measure, it is possible to compare between dissimilar manufacturing and business approaches.

The general approach suggested here is a three stage consideration of energy at the business strategy level. In the first stage, it is essential to set the boundaries and contributing factors for energy consumption. Boundaries will include everything that a manufacturer is responsible for or has direct control over during the entire product/s life time and could extend to the supply chain, providing sufficient information is available. Contributing factors should focus on high level energy consuming tasks such as embodied product energy, impact of energy sources, embodied life cycle energy of the factory infrastructure, post-life product responsibility and life span of manufactured product.

The second stage in the approach requires an understanding of the relationship between different energy considerations, assignment of appropriate variables and development of any relationships between factors. In most cases, it will be useful to evaluate the total energy consumption per product year for which the manufacturer is directly responsible (i.e., not during use cycle). It is not important to fully understand the details of each energy contributing factor, but it is important to understand how certain factors relate to one another. An example of this is described in Section 4.

The third and final stage is to identify the factor(s) that have the largest energy contribution and make improvements in these areas as appropriate.

Obviously, the current approach is generalised but is intended to give guidance for the development of future EM techniques for decisions at the business strategy level. Of key importance is sufficient understanding of the impact of business strategy on energy consumption and the specific actions that can be taken to reduce this reliance on energy.

4. A Case Study for EM Method at the Business Strategy Level

The life cycle approach for considering energy at the business strategy level can be applied to any product, provided that sufficient consideration is given to the contributing factors. The level of detail can be adjusted to allow for different levels of data availability or understanding, but it is important to assess the need for different energy consumption factors within the life cycle of the product.

It may be criticised that consideration of some factors are difficult at the business strategy planning stage. However, it is not necessarily essential to have firm data in order to be able to assess different strategies; sensible assumptions can be used to evaluate the energy implications of business strategies. The following example compares different business strategies for the manufacturing and provision of steel roofing material using energy data from [12]. Considerations for energy consumption should include manufacture of the sheeting, transport, maintenance or replacement and any energy consumption or benefit from end-of-life management. The data used for this case study is shown in Table 2.

Factor	Values
Steel sheet production#	178 MJ/m^2
Transport#	2 MJ/m^2
Replacement section manufacture	3.6 MJ/m^2 year
Maintenance of roof	3.6 MJ/m^2 year
End of life management#	-48 MJ/m^2

#Data from [12].

Table 2. Numerical values used for comparison between PSS and sale business strategies for steel roofing.

A manufacturer may evaluate the benefit with respect to energy consumption of supplying galvanised steel roof sheeting under a product service system (PSS) basis as opposed to the more common make-sell business model. Under a PSS, the building owner does not actually own the roofing material (ownership remains with the producer) but lease it on a fixed term basis (e.g., for the period of occupation of the building) with maintenance costs being covered by the producer. The 'user' simply pays for the use of the roofing. Setting the boundaries of the comparison between manufacturing processes carried out in-house by the manufacturer and the end-of-life management of the galvanised steel sheeting, Table 3 shows the different factors for consideration in this scenario.

Factor	Sale	PSS	Values/Assumptions
Steel sheet production (MJ/m^2)	$E_{x,prod}$	$E_{y,prod}$	$E_{x,prod}$=$E_{y,prod}$ = 178
Transport (MJ/m^2)	$E_{x,tran}$	$E_{y,tran}$	$E_{x,tran}$=$E_{y,tran}$ = 2
Replacement section manufacture (MJ/m^2 year)	$E_{x,rep}$	*0*	$E_{x,rep}$= $E_{x,prod}$/50 = 3.6
Maintenance of roof (MJ/m^2 year)	*0*	$E_{y,mnt}$	$E_{y,mn}$= $E_{y,prod}$/50 = 3.6
End-of-life management (MJ/m^2)*	*0*	$E_{y,eol}$	$E_{y,eol}$ = -48
Lifetime (years)	*z*	*kz*	*z* = 20 years

k, the ratio of the life of the PSS roofing to the life of the customer owned roofing.

*If the manufacturer instigates the recycling of the material, they can justify off-setting any energy benefit against their manufacturing energy consumption.

Table 3. Energy consumption factors considered for comparison between PSS and sale business strategies for steel roofing.

Using the factors from Table 3 in the equation $E_{PY}= (E_E+ E_P+ E_F)/L_P$, the energy per product year can be written for the sale and PSS business strategies, respectively, as $E_{x,py}=((E_{x,prod} + E_{x,tran})/z) + E_{x,rep}$ and $E_{y,py}=((E_{y,prod} + E_{y,tran} + E_{y,eol})/kz) + E_{y,mnt}$.

These two basic expressions can be used to determine the significant contributing factors of both the roofing sale and PSS strategies. Since from the above we can obtain the equality $((E_{x,prod} + E_{x,tran})/z) + E_{x,rep} = ((E_{y,prod} + E_{y,tran})/z) + E_{x,mnt}$, then we can obtain, $E_{y,py}= (E_{x,py}/k)+ (E_{y,eol}/kz)$.

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Using the values from Table 3, and given that it can be shown that $E_{x,py}$ = 9.8 MJ/yr/m^2, we find that, $E_{y,py}$=(7.4/*k*).

Thus it can be shown that if $k > 0.76$, then it will always be beneficial from a manufacturer's energy perspective to opt for the PSS strategy. In the PSS strategy, since the manufacturer generates income from each year the roofing material is in service, rather than from a one-off income generated through the sale of the steel sheeting, the value of *k* will likely be greater than 1. The incentive to prolong the life of the product by the manufacturer means that addition care may be taken in the maintenance of the roofing, at the expense of $E_{y,mnt}$.

Based on the given example, to make the sale strategy more competitive in terms of energy, manufactures could focus on methods of extending the life of the roofing (e.g., by additional coatings) or significantly reducing the embedded product energy (which will likely have a negative impact on life expectancy). As no actual energy is consumed at the business strategy level, energy improvements will ultimately come from the implementation of EM techniques at lower manufacturing levels.

In the given case study, it is possible to introduce additional terms into this comparison which may look at energy implications such as process machinery and infrastructure life cycle energy costs, warranty repair, supply chain PSS, for example, depending on the company's scope and business model.

Using the three stage approach proposed in this chapter it is possible to compare between different business strategies using limited data or assumptions. The output will give an indication as to the energy consumption factors that need to be considered in more detail to ensure the overall minimisation of energy use for manufacturing activities. However, significant work is required by academia and the manufacturing industrial sector to develop more focused EM techniques for the business strategy level.

5. Concluding Discussions

The need for EM and rationalisation within manufacturing has led to the development of a very large number of EM techniques. These techniques cover issues from machine–tool interaction to distribution logistics and supply chain management. A review of a cross-section of EM techniques has revealed a correlation between the manufacturing levels and decision timescale. As a consequence, there are areas of research that have not yet been addressed, such as the life cycle evaluation of production processes and the short-term management of energy supply and supply chain operations. This chapter asserts that there is a requirement for EM techniques to be developed in these currently uninhabited research spaces since manufacturers are continually searching for ways to reduce energy costs and improve environmental performance. Considerations for approaches to developing EM for life cycle impact of production processes include flexible, reconfigurable process chains, factory layouts and upgradability and maintainability. For eco-intelligent factories and reactive supply chains, energy supply security, production flexibility and supply chain agility will form the cornerstones of EM for manufacturers of the future.

In addition, as manufacturers consider more radical ways of reducing their environmental impact and maintaining market share in volatile consumer markets, new business strategies are being considered to generate income in ingenious ways. These new strategies are being developed with economic benefit as the primary focus, but it is also important for manufacturers to consider EM of these strategies to minimise the energy consumption of their activities in the long term. Therefore, building on the existing scope of EM techniques which have focussed on the manufacturing levels, this work suggests that new techniques need to be developed for an additional manufacturing level, namely business strategy, which is positioned above the enterprise level in the hierarchy. The business strategy level has been shown to be slightly different from the other manufacturing levels in that no energy is actually consumed at this level, but energy consumption for products and services are largely defined by decisions at this level. It is therefore reasoned that approaches to EM for business strategies should consider the energy expenditure that the manufacturer has direct control over for the life cycle of the product. This approach allows different business models to be evaluated using the same core framework, even if the strategies are markedly different.

A three stage high level procedure has been described for EM at the business strategy level, which consists of definition of scope and energy contributing factors, identification of interrelationships between energy factors and a comparison of potential strategies and finally a focus on the largest energy consuming factors using techniques from lower manufacturing levels. Of key importance at the business strategy level is that there is no requirement for detailed energy data that may be difficult to obtain at a planning stage. Instead, comparisons may be made between strategies based on a few well-grounded assumptions.

In summary, as manufacturing businesses become more energy aware and seek to remain competitive in highly transient and environmentally focused markets, new business strategies and increased production flexibilities are being explored. The manufacturing industry is evolving for the better, and new EM techniques will be essential in supporting this revolution.

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