

## 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.

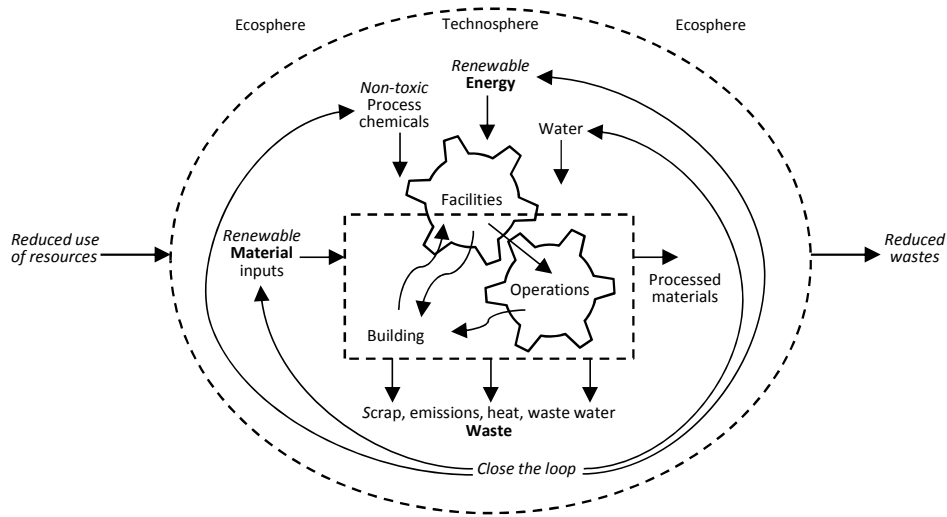


Fig. 1.2.1 Manufacturing (eco)system model with the sub-systems and resource flows (from [24])

## 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.

This ecosystem model is used to define the direction of change needed and objectives to move towards sustainability. Boundaries are drawn following the factory gate. The work focuses on factory-wide improvements to retain the value of resource and avoid environmental degradation. The four strategies mentioned above are usually applied at supply-chain level beyond the control of a single company. This work takes a narrower view and applies the three first strategies at factory level.

The elements modelled are the buildings, the technology components (equipment and processes) placed in and near the buildings, and the resource flows linking all elements of the model (inputs: energy and material including water and chemical; outputs: product and wastes including physical waste accumulating in bins as well as energy waste mostly in the form of heat). All elements of the system are characterised by process data. Table 1.2.1 shows the list of process data and the corresponding real-world information collected by the user (right-hand column).

Some of the process data and profiles can be defined as constraints to determine the minimum requirements (inputs quantity and quality) for the manufacturing processes to achieve their function correctly (product output quantity and quality): mainly production schedule and set points. The other process data and profiles can be functions of these constraints or metered data. Other variables must be defined to characterise the technology elements (equipment and processes, or the transformation processes): capacity or equipment rating, running load (including the minimum/base load and maximum/peak load), the performance/efficiency curve (ratio output/input as function of running load), etc. Other optional information can be added to increase the quality of the analysis, such as equipment age (depreciation time), operating cost, etc.

#### 4 Sustainable Manufacturing Tactics

Sustainable manufacturing practices were collected and analysed to formulate generic tactics. The aim was to abstract the principles/mechanism of the practices in order to apply them to other types of technology and resource. In turn this supports the generalisation of practices.

Sustainable manufacturing practices were collected from two types of sources:

- Research papers with principles and approaches for sustainable manufacturing, sometimes based on a survey of industrial practices, or on analysis of current practices. These sources provided a wide range of practices but few details on the application of the practice or on the technical content of the activities.
- Internet website on best practices, examples from companies. These sources provided more details on the activities and the results from the implementation, but few details on how the improvements were identified or what were the difficulties encountered.

These two types of source gave different information about the activities: some cases provided full reports of initial investment cost, operational and maintenance costs, and annual savings in terms of water, material, energy and cost, while other cases gave insufficient or no information at all on benefits of implementation. Therefore, it is difficult to draw conclusion on trends in the scale of change, the amount of efforts required or the magnitude of the savings. Moreover, all collected cases reported success stories with no mention of challenges, difficulties or barriers to implementation, and no reported case of failure.

Three categorisations were used to analyse the practices and to compare the mechanism for identifying sustainable manufacturing improvement opportunities. The structure chosen for the library of SM tactics has been designed in

Table 1.2.1 List of process data for modelling and their sources

<b>Building model:</b> drawing the infrastructure	
Building geometry / thermal zones	Factory layout (technical drawings)
Construction data	Building construction materials
HVAC systems	Building service system documentation
<b>Qualitative process model:</b> mapping manufacturing operations & facilities	
Technology (process/equipment) geometry	Pictures of equipment/processes (optional)
Technology layout	Factory layout (technical drawings)
Technology attributes/characteristics	Process/equipment specifications
Resource layout	Energy and material path/network layout
Resource characteristics	Energy and material characteristics
List of processes (qualitative product flow)	Manufacturing routings
<b>Quantitative process model:</b> modelling manufacturing operations & facilities	
Production profile (factory-wide), equipment/process operations profile (local), product profile (quantitative product flow)	Production schedules
Technology set point/demand profiles	Equipment and process set points, demand, running load
Technology control profiles	Controls (controllers, valves, etc.)
Resource usage profiles	Facility equipment & manuf. process cons. (metered data)
Resource supply profiles	Facility equipment generation (metered data)
Waste profiles	Facility equipment & manuf. process waste generation
Total inputs to the system (check model completeness)	Total inputs to the system (energy/water bills and BOM)
Energy and mass balance (for missing data)	Thermodynamics for resource transformation process
Link technology to HVAC system	Thermal transfer to space/building
Link technology to bins (waste profile, energy and mass balance)	Waste data (if available)
<b>Optimised process model:</b> improvements implementation	
Controller functions (for simulation purpose)	Control strategy
Bins/recycling repositories	Recover, sort, collect, reuse, recycle
Modification to technology (process/equipment)	Equipment/process management or change
Modification to resource flow	Resource management or change

order to ease the implementation of the library directly into the simulation software (THERM tool). The objective is to identify Sustainable Manufacturing improvement opportunities in a structured and systematic way.

The first categorisation is based on the type of modification (organisational or operational **Manage**; technical or physical **Change**) and the elements targeted (focus on **Resource** or **Technology**). Tactics were listed against these four labels in the first categorisation system as shown in Table 1.2.3. The second categorisation distinguishes the nature of the flow affected by the practices (inputs: energy, water, material; or outputs: air emissions, wastewater, solid waste) and allows to filter practices based the flow type and targeted benefits (energy reduction, CO<sub>2</sub> emissions abatement, water conservation, toxicity, “zero waste”, etc.). Finally, the third categorisation identifies the functional responsibility to implement the improvements in the factory. Similarly to the second categorisation, it is used to narrow down the search of practices to specific functional areas of the company according to the responsibility of the people involved in the improvement activities.

By attempting to classify all the cases, the type of activities in some cases appeared be out of the scope of this study (off-site activities or changes in the way of thinking/managing the production rather than physical changes in the factory). Therefore some practices were excluded from the final database for formulating generic tactics. Table 1.2.2 summarises the distribution of practices across strategies and the nature of the flow targeted by the improvement activity (note that one practice can fit under multiple labels at once). The tactics were identified by classifying the cases based on their commonalities, the drivers of change and the mechanisms for implementing the practices. As the tactics are generic and cover various technological solutions and MEW flows, the number of tactics formulated was as low as 20 (Table 1.2.3). In other words, it means that a large number of practices can be identified by looking at few variables and using simple rules.

This first categorisation helped to check the completeness of the tactics library. Each generic tactic was then analysed using the manufacturing ecosystem model (Fig. 1.2.1) and energy/waste hierarchy (strategies adapted from [29–31]) to prioritise the tactics by identifying at which stage the tactics would be implemented.

The material waste hierarchy is well-established and is typically represented by a pyramid with disposal at the bottom rising up through the ‘R’ levels of recovery, recycling, reuse, reduction and finally prevention at the top. Prevention is the preferred option with disposal the least favoured.

Table 1.2.2 Distribution of practices

	1 Manage resource	2 Change resource	3 Manage technology	4 Change technology	Energy	Air emissions	Water	Wastewater	Material	Solid waste	Total no. of practices
<b>1 Prevent</b>	1	0	2	4	2	0	0	2	2	0	<b>6</b>
<b>2 Reduce wg<sup>a</sup></b>	10	25	34	6	18	2	9	6	23	20	<b>62</b>
<b>3 Reduce ru<sup>b</sup></b>	10	6	24	6	11	3	5	2	13	7	<b>36</b>
<b>4 Reuse</b>	17	29	0	8	9	2	8	13	9	17	<b>37</b>
<b>5 Substitute</b>	5	30	6	50	30	7	10	13	26	15	<b>72</b>
<b>Total</b>	<b>43</b>	<b>90</b>	<b>66</b>	<b>74</b>	<b>70</b>	<b>14</b>	<b>32</b>	<b>36</b>	<b>73</b>	<b>59</b>	<b>213</b>

<sup>a</sup>waste generation; <sup>b</sup>resource usage

Analogous energy hierarchies also exist to prioritise improvements in energy resource use, again with prevention at the top and going down through the levels of reducing, reusing, etc. [32, 33]. Such hierarchies are distinct from the source of energy supply, e.g. prioritising renewable over fossil fuel to decarbonise through substitution.

It is appropriate therefore to base the prioritisation of MEW flow improvement options on these hierarchies.

- Prevention by avoiding resource use: eliminate unnecessary elements to avoid usage at the source, stop or stand-by equipment when not in use.
- Reduction of waste generation: good housekeeping practice, repair and maintain equipment.
- Reduction of resource use by improving 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.
- Reuse of waste as resource: look for compatible waste output and demand, understand where and when waste are generated and whether it can be used as resource input elsewhere considering the complexity of the system.
- Substitution by changing supply or process: renewable and non-toxic inputs, change the way the function is achieved to allow larger scale improvements.

Table 1.2.3 List of generic tactics

<b>1 Manageresource</b> 1a Align resource input profile with production schedule 1b Optimise production schedule to improve efficiency 1c Optimise resource input profile to improve efficiency 1d Synchronise waste generation and resource demand to allow reuse 1e Waste collection, sorting, recovery and treatment	<b>2 Changeresource</b> 2a Remove unnecessary resource usage 2b Replace resource input for better one 2c Add high efficiency resource 2d Reuse waste output as resource input 2e Change resource flow layout
<b>3 Managetechnology</b> 3a Repair and maintain 3b Change set points/running load, reduce demand 3c Switchoff/standby mode when not in use 3d Monitor performance 3e Control performance	<b>4 Changetechnology</b> 4a Remove unnecessary technology 4b Replace technology for better one 4c Add high efficiency technology 4d Change the way the function is accomplished 4e Change technology layout

Table 1.2.4 Strategies and tactics

<b>1 Prevention</b>
1a Align resource input profile with production schedule
2a Remove unnecessary resource usage
3c Switch off/standby mode when not in use
4a Remove unnecessary technology
<b>2 Reduction (waste generation)</b>
1e Waste collection, sorting, recovery and treatment
3a Repair and maintain
<b>3 Reduction (resource use)</b>
1b Optimise production schedule to improve efficiency
1c Optimise resource input profile to improve efficiency
3b Change set points/running load, reduce demand
3d Monitor performance
3e Control performance
2e Change resource flow layout
4e Change technology layout
<b>4 Reuse</b>
1d Synchronise waste generation and resource demand to allow reuse
2d Reuse waste output as resource input
<b>5 Substitution</b>
2b Replace resource input for better one
2c Add high efficiency resource
4b Replace technology for better one
4c Add high efficiency technology
4d Change the way the function is accomplished

## 5 Improvement Methodology

The improvement methodology must follow a sequence that links the tactics to the process data used to model the manufacturing system. Interestingly, the order in which improvements can be identified does not follow the prioritisation order presented earlier. This presented a major challenge for developing the tool and the improvement methodology. The difficulty for identifying an improvement is not reflecting the difficulty for implementing it. On the contrary, in some cases bigger efforts in data collection are required to identify “low-hanging fruits” (e.g. stop and repair equipment) whereas replacing elements of the system at high cost can be identified quickly (e.g. black-listed resources or old inefficient equipment). Keeping this challenge in mind, this section presents the improvement opportunities following the prioritisation order rather than the first possibility identified.

To access the **prevention** types of improvement, it is important to note that the “change” tactics (2a and 4a) can be difficult to identify as they require expert knowledge about the process to identify the resources or process being used unnecessarily and therefore can be removed. The “manage” tactics (1a and 3c) are comparing patterns between data defining the constraints (production schedule or product profile) and the resource usage or equipment controls to identify when they can be stopped or put in stand-by mode.

The **waste reduction** improvements focus on waste outputs to find a way to reduce losses or maintain the value of the output, even when it is a waste (residues, unwanted by-product, etc.). These improvements are considered as relatively easy since they allow quick savings in resource and cost with limited efforts. But manufacturers’ knowledge about their waste is often limited and for the waste patterns to be identified, a thorough data collection must be conducted. The

focus is on processes which are the largest resource consumers and waste generators.

The **resource use reduction through efficiency** improvements focuses on the resource inputs to find a way to increase the use productivity. The most difficult improvements can be to challenge the set points or modify the production schedule as these can only be done with deep knowledge of the processes and production system. The other types of improvement are comparing patterns in demand and supply profiles both in a static (logic tests) and dynamic (simulation) way. The logic tests are comparing the magnitude of supply to the minimum requirements to better match the demand-side (e.g. pressure of compressed air, temperature or cooling water, etc.). Simulation is also used to optimise the timing of the resource flow which can result in overall efficiency improvements (avoid peak consumption or reach the optimum demand level to match equipment high efficiency point of use). The simulations requires a large amount of data, thus those improvements can be identified only based on advanced analysis of the system.

The **reuse** types of improvements are focusing primarily on the waste flows and look for opportunities to reuse waste output as a resource input. The use of a simulation tool is an important asset to allow systematic search for compatible waste and demand in the system taking into account the complexity of the system modelled, the timing of the flows and the spatial dimension. These improvements are done last as wastes must be eliminated or reduced before looking for reuse opportunities.

The **substitution** improvements can be identified at early stage of the modelling by recognising inefficient components (the basic information about component capacity, efficiency and age of equipment) or black-listed resource being used (toxic, non-renewable, non-reusable, etc.). This type of improvement was the most commonly found in the case collection: replacing a piece of equipment or a process by a more efficient one or a less environmentally damaging one is a quick way to increase the sustainability performance but likely at high cost. They involve large scale changes by improving the source of supply and using high efficiency technology but they also reduce more dramatically the environmental impact of the manufacturing activities. The tactics are linked with the database of best practices to suggest alternative resources or technological solutions.

## 6 Application Example

Prototype applications were conducted with industrial partners to model the manufacturing operations and facility performance before improvements to test how the tactics would identify them. Fig. 1.2.2 shows a graphical example of an air supply system modelling based on the manufacturing ecosystem model. The diagram shows the MEW flows across the system as resources are being consumed to draw air through the processes by fans to achieve the manufacturing process set points (air temperature and humidity). The MEW flows are modelled from supply source to treatment (shaded boxes), to the equipment and process being investigated (clear boxes). The process data collected were used to characterise each element of the system: input and output profiles, air and water properties before and after each process, equipment capacity and actual running loads, process demand profiles and set points.

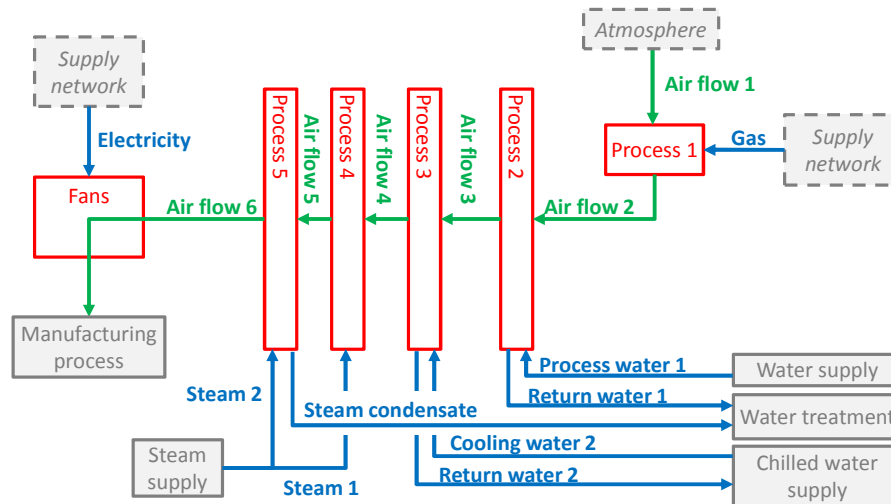


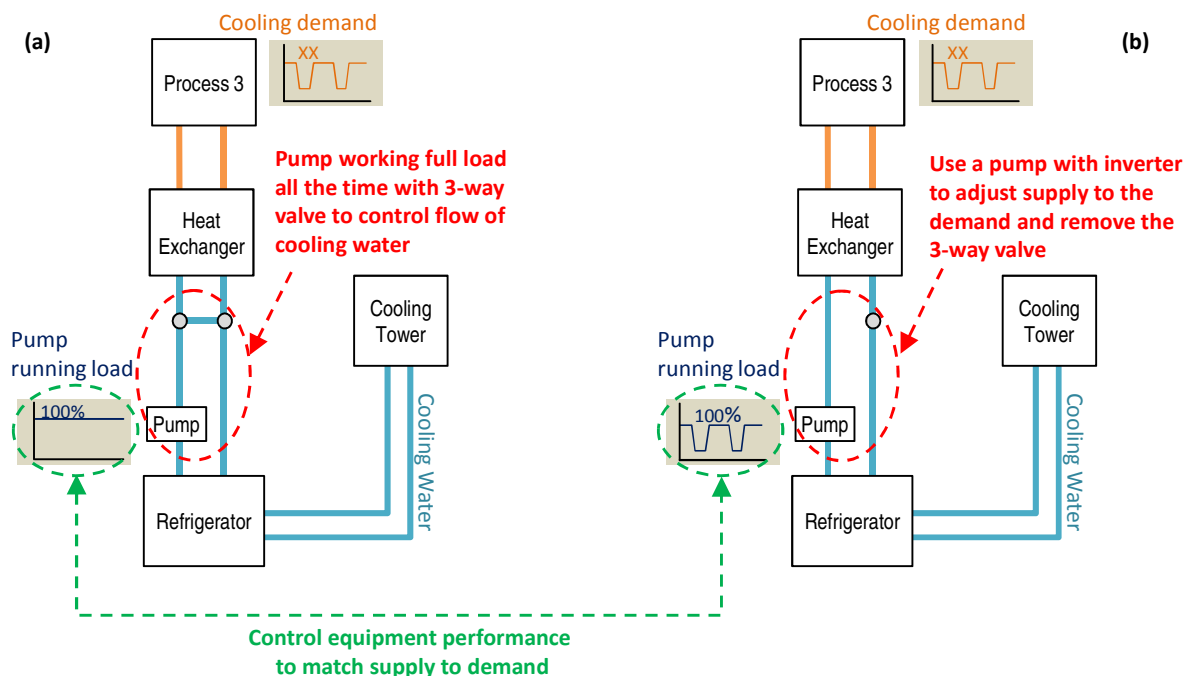
Fig. 1.2.2 Modelling of an air supply system

Each process can be further detailed by creaking down a box of the diagram into a new diagram to show more details. For instance, Fig. 1.2.3a shows a more detailed view of the chilled water supply. Depending on the data available—and therefore the process data used to characterise the system's components—different tactics are used to compare profiles, identify mismatch and inefficiencies, and suggest improvement options.

Following the sequence for improvement strategies and tactics as listed in Table 1.2.4, the prevention tactics were used to compare resource usage profile and production schedule, i.e. check whether resources were consumed during non-production hours. Then a comparison of total supply and sum of all usage allowed a check on completeness of the model

and identify excessive losses occurring between supply and usage. In this particular example, the prevention and waste reduction activities were already applied.

The next group of tactics in the sequence is the resource use reduction. Tactics 3b and 3e identified an improvement opportunity by comparing the cooling water system performance (water temperature and pump running load, and therefore cooling water supply) to the cooling demand profile of process 3. As illustrated in Fig. 1.2.3a the pump was running full load all the time when the demand was significantly varying. A first improvement opportunity was identified by comparing the temperature of the cooling water input and the process set points (or cooling requirements). After performance assessment, the water tank temperature

Fig. 1.2.3 Chilled water system. **a** Before improvement, **b** after improvement

was increased resulting in significant energy savings to maintain the cooling water temperature. Additional improvements were implemented on the chiller sequence control as well as inter-shift and weekend switch-off, resulting in a total saving of 40% energy for the chilled water system.

An energy and water reduction opportunity was also suggested as illustrated in Fig.1.2.3b: improve the equipment control to better match the supply to the demand. In this particular case, using an inverter with the pump allowed the water input to match the demand for cooling water by reducing from oversized and continuous supply flow to variable adjusted supply level, resulting in a total of 75% water savings and additional energy savings on the pumping system.

The same system was modelled in two different ways to test the access to more tactics using other process data. In a second variant, the pump characteristics (running capacity and performance curve) were used to identify a substitution improvement (tactic 4b) where the pump would be replaced with variable speed one and adequately sized for the process demand as the current one was oversized in anticipation of production expansion, overlooking the energy savings accomplished over the years which decreased the energy demand while increasing production level.

This application example demonstrates that it is possible to identify improvements in a structured way using modelling of MEW flows to connect the manufacturing facilities and operations and gain a better understanding of the interactions between them. The modelling tool developed can assist manufacturers in assessing the resource productivity with a systems perspective and help to manage resource flows more sustainably.

## 7 Concluding Remarks

This paper introduced sustainable manufacturing tactics which can support manufacturers in undertaking the journey towards sustainable manufacturing. Cases were collected from literature and the practices classified using various categorisation systems and hierarchies. Generic tactics were formulated to cover a wide range of sustainable manufacturing practices and dictates the rules for identifying improvements in a structured and systematic way. The practices can be formulated with only 20 generic tactics and therefore be identified using few simple rules.

An application example showed that tactics enable the how question to be answered and help identify improvements opportunities. Improvements can be prioritised using the waste and energy hierarchies: high efficiency technology or renewable resources are not necessarily the ultimate answer or "sustainability silver bullets" as there are many options to consider before coming to substitution of technology and resources.

Modelling is used to guide the user through the steps of collecting data and understanding their manufacturing system before undertaking improvement activities. The manufacturing ecosystem model captures the resource flows through the factory using the manufacturing ecosystem model developed by the authors. The work focuses its analysis to what happens within a factory or a part of it (gate-to-gate). The authors recognise the need for a more holistic perspective on industrial systems and on society if sustainability is to be achieved. The boundaries have been set so that the manufacturer has full control on all elements

in the studied system. The work excludes certain aspects of sustainability such as social and economic impact, since they are considered as positive side-effects of the work conducted rather than objectives. Also, the resources here are only energy, material, water, chemicals, etc. and not capital, employees, etc.

The improvement methodology was developed to guide the user to opportunities using the energy and waste hierarchies, and help selecting the most appropriate options based on defined targets. Disposal, which is at the bottom of the hierarchy, was not used as it is not considered as an improvement, but rather the least desirable option obtained once the higher levels of the hierarchy have been exhausted. The work showed that it is possible to identify sustainable manufacturing improvement opportunities in a systematic way using modelling of manufacturing system.

Future work includes an extension of the practices database and software development [23] for integrated modelling of MEW resource flows to identify improvement opportunities towards sustainable manufacturing through combined analysis of manufacturing operations, supporting facility systems and production buildings.

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