025-1302

Modeling buildings, facilities and manufacturing operations to reduce energy consumption

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POMS 23rd Annual Conference
Chicago, Illinois, U.S.A.
April 20 to April 23, 2011

Abstract
Traditionally, manufacturing facilities and building services are considered to be supplementary to manufacturing operations. Manufacturing operations use and discard energy with the support of facilities. Additionally, these disciplines have been pursued independently to date; the design and improvement of buildings and manufacturing systems typically carried out in isolation. Therefore improvements in energy and other resource use to work towards sustainable manufacturing have been sub-optimal. This paper presents research in which buildings, facilities and manufacturing operations are viewed as inter-related systems. The work documents practices, tactics and specifies modeling tools, that enable integrated analysis of manufacturing site energy and resource use. The objectives are to improve overall energy efficiency and to exploit opportunities to use energy or other waste from one process as potential inputs to other processes. The novelty here is the combined simulation of production and building energy use and waste in order to reduce overall resource consumption. The paper presents a literature review, develops the conceptual modeling approach and introduces the prototype with industrial cases to support activities towards sustainable manufacturing.

Introduction
The Bruntland report (WCED 1987) defines sustainable development as meeting the needs of the present generation without compromising the ability of future generations to meet their own needs. Focusing on sustainable manufacturing there is the need to recognise the triple bottom line of social justice (people), environmental quality (planet) and economic prosperity (profit) (Elkington, 1997). There is significant work underway in both academia and industry to develop tools and techniques for sustainable manufacturing and apply them for tangible benefit. As a result of rising prices and concerns over energy security and climate change, energy is a major focus. Documented cases and achievements presented on corporate websites show that significant benefits can be obtained. However, it is not until a sustainability mindset is adopted that the opportunities can be identified in the first place.

Sustainable manufacturing (Rahimifard & Clegg, 2007; Seliger, 2007; Kumazawa & Kobayashi, 2003) (based on environmental conscious manufacturing) is broad in scope, taking a high level view of manufacturing and including the triple bottom line elements. Sustainable manufacturing looks beyond the boundaries of one factory and considers the entire material cycle from material extraction through processing and use to subsequent disposal (O'Brien, 1999; Allwood, 2005). Most research in sustainable manufacturing has focused on product design and product end-of-life with relatively little research activity focusing on improving manufacturing systems. Subsequently there is an absence of methodologies for manufacturers to generate improvements within their own facilities (Despeisse, 2010), this is despite the financial benefits possible by integrating sustainable manufacturing into corporate management (Srinivasan, 2011).

Buildings consume a significant amount of energy to provide heating, cooling, ventilation, lighting and power. Individuals in both buildings and manufacturing systems disciplines use methodologies to guide design and reduce resource use including simulation. Buildings and factory facilities are typically suppliers to manufacturing operations and are managed according to different metrics. There is significant potential for improvement by integrating these areas but there is currently a lack of knowledge, skills and tools. Opportunities exist to develop methodologies and new ways of visualisation based on ICT to improving production activities (Garetti & Taisch, 2012).

This paper describes tools for manufacturing buildings and manufacturing systems and the methodologies to support their improvement. In the absence of available tools and methods, the paper presents an approach to combine these areas. Prototype work on integrating them along with sustainable manufacturing practices is introduced.

Modeling tools for sustainable buildings and manufacturing

Perhaps as a consequence of the absence of methodologies to transform manufacturing systems, there is a lack of software tools, such as simulation, to support the design and analysis of sustainable industrial systems. As with the adoption of lean methodologies and 'lean/green' techniques (e.g. Ball et al., 2009), there have been incremental developments in simulation for discrete manufacturing that include energy modeling. As lean methods and manufacturing simulation tools typically capture the visible value-adding processes, significant energy consuming processes in a factory are ignored. The facilities that supply steam, air and other services are rarely included. Additionally the building that surrounds the manufacturing operations and part of the manufacturing facilities is ignored and considered separately from manufacturing system design.

Building design and refurbishment is regulated and defined by detailed standards and metrics, particularly building codes and voluntary standards such as BREEAM and LEED. As with manufacturing systems design, building design is supported by improvement methods and guiding tools. The tools incorporate sophisticated modeling for areas such as comfort and energy performance.

Currently there are no commercially available tools for manufacturers to assess environmental performance, identify improvement areas and help suggest concrete actions across the breadth of the application area just described. Additionally, there are few examples of research (Ball et al., 2009; Herrmann & Thiede, 2009; Hesselbach et al., 2008; Michaloski et al., 2011) to bring these domains together. Such work presents conceptual design and narrow simulation but does not offer as much benefit as the combination of improvement methodologies and integrated buildings, facilities and production system modeling.

Any sustainable manufacturing modeling tool must be capable of modeling the interaction between the production system and its physical environment – firstly the building itself (including the effect of external factors such as weather data or surrounding buildings) and then the locality. For example, sustainable manufacturing tactics include the potential to use local waste to power production processes, or the transfer of waste heat from production to other local businesses.

Modeling approaches

A traditional view of a manufacturing system operation is one that converts raw materials into useful outputs. Manufacturers have always sought to minimise the waste and the advent of lean manufacturing has led to a better understanding of the breadth of waste types and the creation of accessible tools to help reduce them.

Energy is consumed in factories to add value to the materials being processed and also to provide an acceptable working environment for staff in terms of heat, light and air quality. As with the arrival of lean techniques to reduce waste materials and time, manufacturers are increasingly looking at energy flows to reduce waste.

Whilst material and energy are both types of resource inputs it is helpful to name them separately to enable sufficient emphasis to be placed on them. Material inputs include raw material for the products as well as consumable resources including water, chemicals, gases and packaging, see Figure 1. Modeling the material, energy and waste flows (Ball et al., 2009) provides a foundation upon which to build improvement methodologies and simulation tools.

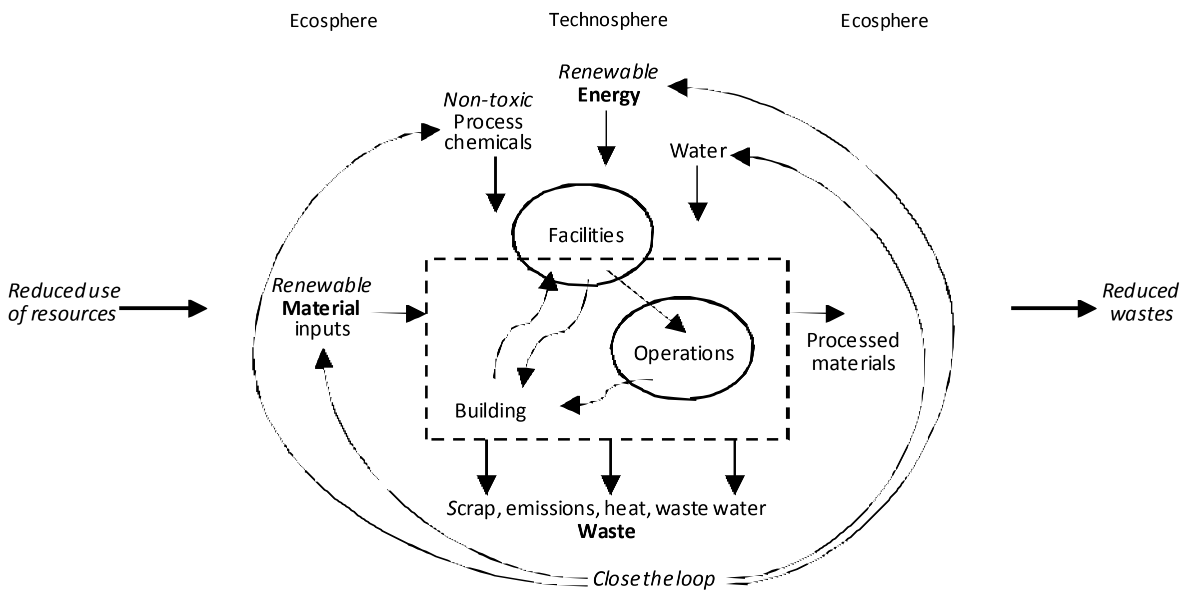

Figure 1. Resource flows in a manufacturing system

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

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. (Hope, 2008; Waltniel, 2009). 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 any improvement of material, energy and waste improvements on the levels of the material and energy waste hierarchies.

Having established a priority for preventing use before reducing use, then reuse and dissipate waste energy, the next step is to establish what actions are appropriate for prevention, reduction, substitution and reuse. In part this can come from common sense examination of resource flows and equipment use, e.g. switching lights off when not needed. However, once obvious actions have been carried out then assistance is required to guide further analysis and identify more subtle changes.

There are many examples of improvements on company websites, government funded repositories, trade publications and academic publications. In general good practices that can be copied or adapted are not available in a structured format for other manufacturers but there are examples of functional repositories (e.g. CEC, 2011; CO2PE!, 2011). There is work ongoing to group practices according to improvement focus (energy, air, water, materials) across the material lifecycle stages (Despeisse et al., 2012) that can provide examples of practices in a more user-focused, accessible format.

Ultimately good practices are accessed more effectively in terms of *how* to tackle an improvement than *what* was done in specific companies (Waltniel, 2009; Despeisse et al., 2011). For example, rather than finding an *example* of switching a machine off at the end of a shift, it is better to understand the *principle* (or *tactic*) of aligning energy use with machining. This may prompt switching off the machine during the shift as well as at the end of the shift. Examples of energy flows and different tactics used to reduce net consumption are shown in Figure 2. For example the figure shows sankey diagrams of how energy flows in an original system and through the application of tactics, better management of the resources or change of technology that result in less consumption can be suggested to reduce input and losses.

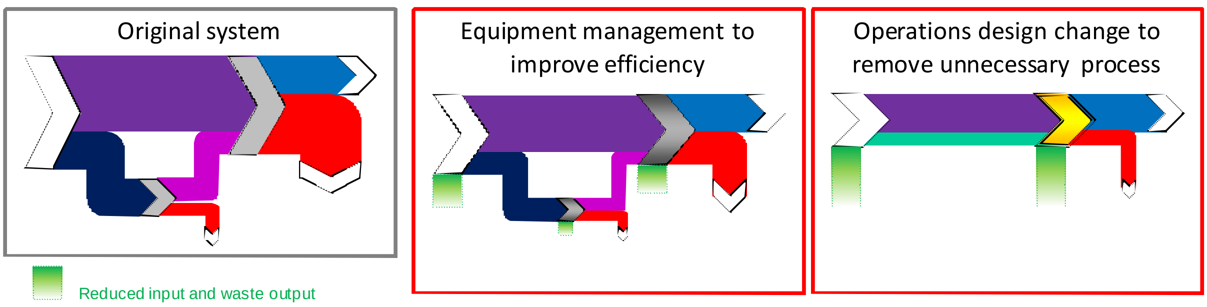

Figure 2. Sankey diagram representations of different tactics to reduce energy consumption.

Returning to the waste hierarchy, prevention activities at the top are principally a technical and local question (e.g. whether machines can be powered down and returned to operating conditions efficiently (Waltniel, 2009; Lunt & Levers, 2011) and without considering the effect on surrounding production equipment and building (Oates et al., 2011a). As prevention and reduction type improvements are exhausted then reuse and recycling improvements must be sought (Waltniel, 2009). This implies a wider perspective to identify interaction with other parts of the production system, which may then include facilities and buildings.

Within most manufacturing operations (especially those that can be considered as discrete) material and energy flows vary over time. For energy the 'quality' will also vary (e.g. production of waste heat at a range of temperatures). To understand the interaction of material and energy changes through time and space dynamic modeling is a possibility (Ball et al., 2009). Manufacturing simulation tools are commonly used in modeling materials over time and building simulation tools are well established to model energy use and dissipation over time and space.

The combination of the two is therefore potential very powerful. For example, they could be used together to understand whether waste heat from air compressors could be used for pre-heating water or whether hot air vented at the end of a process cycle could be used to contribute to space heating in winter. Simulation would be used to understand the potential contribution of waste reuse considering the complexity of the system and the timing of the heat availability, timing of the heat demand, the heat transfer, spatial aspects, etc.

A software system that combines building simulation with an operational model might use tactics to refer the user to sustainable manufacturing practices. For example, if the simulation tool was able to model production activity and energy consumption then a comparison of the two could be made and a mismatch could be highlighted. If it was deemed using tactics that energy was being used unnecessarily when there was no production then a link could be made to manufacturing practices to illustrate what other companies did to implement a solution.

The research project underway by the authors is developing a tool that can help identify improvements through integrating modeling tools, tactics and a database of practices. These sustainable manufacturing tactics have to account for location and time, as well as production process, in a manner that is not currently supported by either manufacturing process simulation tools, or building energy tools.

Prototype

Based on a leading commercial building performance analysis package (IES VE), production facilities modeling using Matlab and the International Building Physics Toolkit (Oates et al., 2011b) and a library of tactics and manufacturing practices (Despeisse et al., 2011) development of the prototype is well underway (Ball et al., 2011). One prototype application has been completed with one industrial partner and another is underway with another industrial partner. Figure 3 illustrates conceptually one of the prototype applications based on the manufacturing eco-system model (Despeisse et al., 2011).

Figure 3 shows the material, energy and waste resource flows across the manufacturing operations, manufacturing facilities and manufacturing building. The flow of product materials and other resources is from source to equipment and beyond. Resources are preserved as they change form (including to thermal energy). The activities are grouped according to operations, facilities and building (some facilities are outside the building concerned). Figure 4 shows graphs of intermittent product flow and continuous resource flow results from the simulation model. Using tactics (Despeisse et al., 2011) the two sets of results can be compared to seek energy reduction opportunities by switching off equipment when there is no production (shaded area of lowest graph).

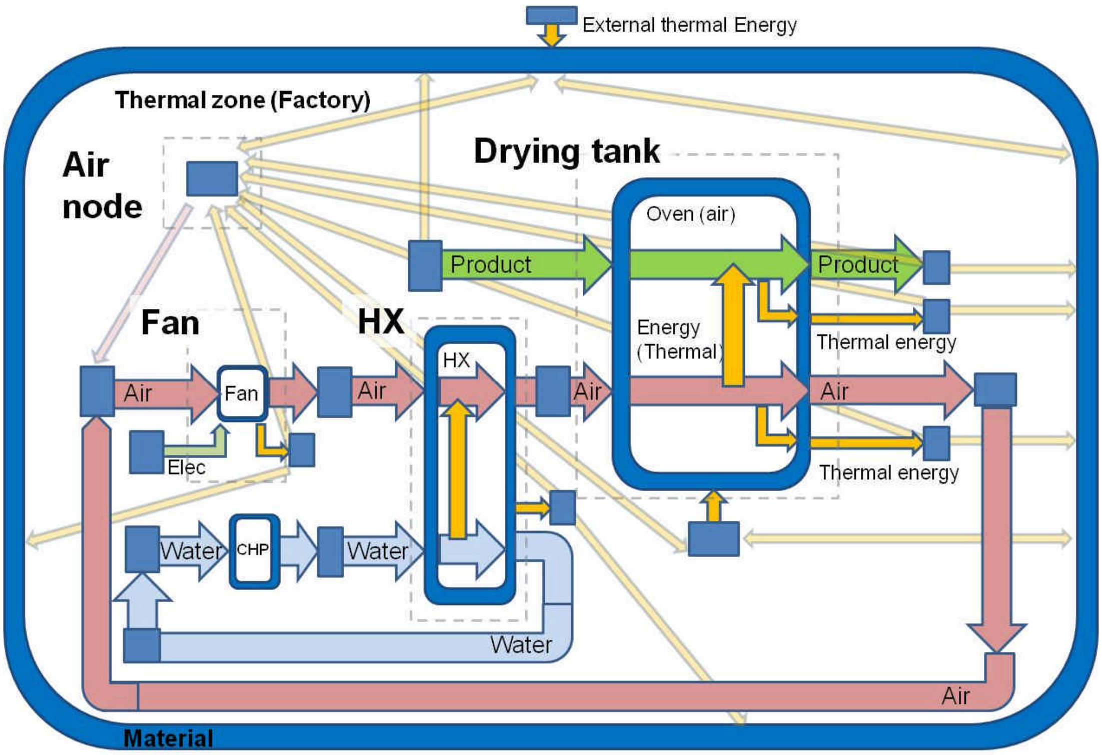

Figure 3: Graphical representation of a drying tank and its subsequent equipment defined by its location (from Oates et al., 2011a)

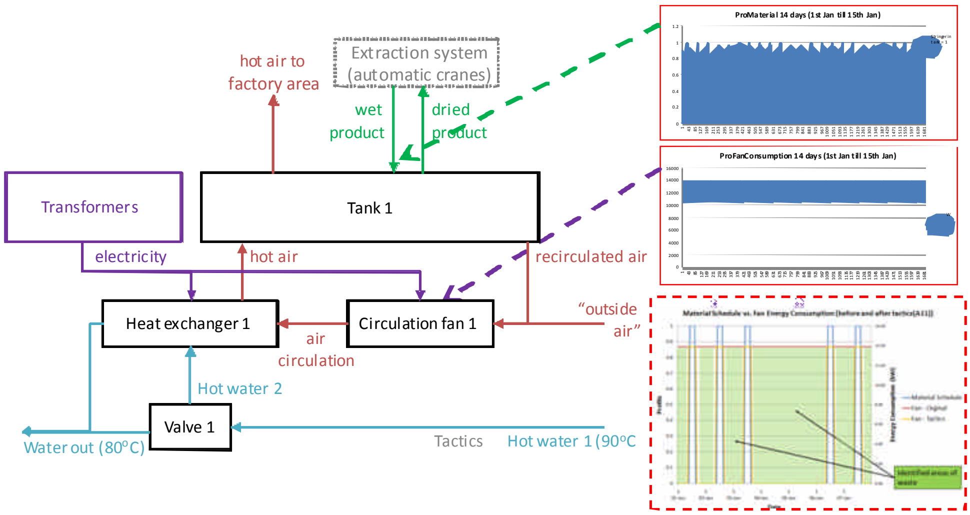

Figure 4: Linking process modeling results to tactics

At the prototype stage the product flow through the operations is modeled using standard discrete event simulation software that provides production profiles to the building performance analysis package. The building performance analysis package will simulate the energy flows and the production flows over time and present the subsequent location, timing and quality of the wastes.

Conclusion

This paper has examined work carried out in the field of sustainable manufacturing and its relationship with building and service design. It has been observed that these two disciplines largely independently on sustainability projects, potentially missing important opportunities for better overall solutions. The design, operation and improvement activities across this broad area utilise different skills, different improvement approaches and different software.

The paper has documented the concept of a tool and supporting methods that could be used to combine the analysis of production systems, ancillary support systems and production buildings. In turn broader and more informed decisions could be made on reducing overall material, energy and resource flows by reducing inputs and reusing wastes.

Future work will encompass software development for novel modeling functionality, integration of software workflows to match the activities of the improvement teams and integration of best practices available from manufacturers.

Acknowledgements
The authors would like to thank those making important contributions to this work including the UK's Technology Strategy Board (TSB) and other individuals in Airbus, IES and Toyota contributing to the TSB funded THrough-life Energy and Resource Modelling (THERM) project.

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