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Towards a framework for energy-aware information systems in manufacturing

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ABSTRACT

Environmental concerns, stricter legislation and inflated energy costs, together yield energy efficiency as an important pillar for virtually every industrial sector. Mindful of this challenge, ISs can act as enablers of energy-based management and intelligent decision support. Based on empirical evidence through two case studies combined with the design of a system prototype, this paper identifies those major functionalities that suffice to characterize an IS as 'energy-aware' in manufacturing. The functionalities are classified into two broad categories: (a) energy monitoring and (b) energy-aware analytics and are then combined into a high-level architecture. As a prerequisite for deploying such functionalities, this research presents also an approach integrating energy and operational information flows. Beyond that, the technologies that support the real-time and large-scale handling of energy data are provided. Our effort scales up to introduce a generic framework of a case-independent energy-aware IS.

1. Introduction

Public and industry concerns over energy efficiency and environmental sustainability have grown considerably over the last decade. Particularly in the manufacturing sector, energy efficiency becomes an even more important pillar, given that manufacturing accounts for 84% of energy-related industrial CO_2 emissions and 90% of industrial energy consumption [1]. Despite these figures, environmental sustainability practices have traditionally been viewed as a 'cost of business', and positioned as a voluntary responsibility of companies. Nowadays, this perception is changing in the light of stricter legislation, industrial standards and rising energy costs [2]. Hence, companies are required not only to adopt a strategy of minimal environmental compliance, but also to treat sustainability practices as a catalyst for innovation. Furthermore, consumers become more aware on whether the products they purchase come from a sustainable source or have been produced through eco-friendly methods, or the corresponding supply chain operations (production, transportation, storage, etc.) guarantee minimum environmental impact [3]; betraying the consumers' confidence may, in the long term, damage a company and its brand image thus yielding its economic collapse [4].

Under the key drivers of legal compliance, energy costs' inflation and customers' increasing ecological awareness, the manufacturing sector has made continuous advances toward energy efficiency. Still, the economic benefits arising from energy efficiency have not been fully exploited [5–8]. Both academic and business studies indicate that there is an "energy efficiency gap" and highlight that there are strong barriers which impede energy-efficient manufacturing. Information systems (ISs) have a strong potential against such barriers by acting (a) as a tool for monitoring energy consumption and carbon emissions thus pinpointing areas for savings [9] and (b) as the basis for energy-based optimization and intelligent decision making [10]. Mindful of this potential, many existing enterprise systems have been enhanced by energy management capabilities. However, these capabilities are limited to energy monitoring, analysis and reporting, i.e., they still lack sophisticated control techniques [2]. It is typical for a stand-alone energy management system (EMS) not to support management decisions in a coherent way due to the lack of integration of information from shop-floor to top-floor [11,12]. Moreover, such systems cannot combine energy consumption with 'traditional' performance indicators like cost or delivery time [2,9,13–15]. Thus, managing distributed and delocalized manufacturing information regarding energy efficiency remains an issue to be addressed; alternatively stated, there is a gap, with respect to energy-awareness in manufacturing, between the solutions available and the actual implementation.

To bridge this gap, academic effort has been structured mainly around "Energy Informatics" as the subfield of ISs investigating "how ISs can be used to reduce energy consumption" [16]. That is,

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Energy Informatics is concerned with analyzing, designing and implementing systems to increase the efficiency of energy demand-and-supply systems. This type of ISs should collect and analyze energy data sets, integrate energy flows with other information flows, support optimization of energy consumption and contribute to energy efficient business processes [16]. Let us hereafter refer to this type of IS as "an energy-aware IS". Although this academic context emphasizes the role of ISs in energy efficiency, the specific functionalities in an energy-aware ISs that are best suitable for delivering meaningful impact remain rather unexplored [16]; this issue can be disassembled into the following questions:

- How can an IS integrate the various information flows needed in order to increase energy efficiency?
- Which elements comprise an energy-aware IS?

Hence our main motivation is to address the above, with a particular emphasis on manufacturing, by:

- identifying a set of basic industrial requirements for an energy-aware IS;
- identifying the information flows that should be integrated by an energy-aware IS;
- proposing a compact, yet exhaustive, set of functionalities to be integrated by an energy-aware IS;
- suggesting a framework that includes the key elements of an energy-aware IS;
- discussing some specific technological approaches for the implementation of an energy-aware IS.

The remainder of the paper is structured as follows. Section 2 offers a justification for the relevance of this work by drawing upon the literature on two primary research strands: the enabling role of ISs for energy management and decision support and the integration of information flows in manufacturing. Section 3 describes the research focus and methodology adopted. Section 4 presents the industrial requirements obtained for an energy-aware IS and the proposed data model integrating all necessary information flows. Section 5 presents the system functionalities that should be supported by an energy-aware IS, along with the proposed architecture and certain data interfaces. Section 6 steps us to propose the framework for energy-aware ISs, while Section 7 elaborates on a more technical view to describe some core technological approaches for the implementation of such an IS. Finally, Section 8 provides concluding remarks along with some limitations and implications for future research.

2. Research background

2.1. ISs as enablers of energy efficiency manufacturing

Mindful of the enabling role of ISs for energy efficiency, today's IT providers, especially in the Enterprise Resource Planning (ERP) sector (e.g., SAP, IBM, Microsoft) have already refined their existing solutions to capture this potential. This means supplementing their existing enterprise systems by energy management capabilities (e.g., SAP Industrial Energy Management, Microsoft Dynamics AX/NAV). However, these solutions mainly cover meter management along with energy and footprint data monitoring–analysis–reporting, while lacking sophisticated intelligence capabilities. There are also stand-alone energy management solutions (e.g., eSight M&T/EMS, EnteGreat's Accelerator Manufacturing EMS, EnergyCap) that remain of limited impact unless integrated with manufacturing execution systems (MES) [17,18]. Hence our argument that ISs may enjoy a solid role as enablers for energy efficiency only if meeting, in addition, most of the following requirements.

2.1.1. Broader level of energy monitoring

Achieving energy efficiency in manufacturing requires a holistic view spanning all parts of the production system (product, processes and resources) and on different layers (or levels) from machine or process step to enterprise level and supply chain externalities [19–21]. Karnouskos et al. [17] highlight the need to correlate energy data gathered from all layers of an organization and develop holistic energy efficiency strategies. A recent study [22] proposes a broad division of energy monitoring based on the level of application (factory, department and unit process level). From a product viewpoint, another study [23] proposes a novel approach for modeling the detailed breakdown of energy required to produce a single article, the so-called Embodied Product Energy framework. Adopting a temporal perspective, the work of Vijayaraghavan and Dornfeld [18] is motivated by the need to conduct energy monitoring and decision making across different levels of analysis (ranging from the entire enterprise to the tool–chip interface) and across multiple temporal scales (ranging from several days at the enterprise level to micro-seconds at the tool–chip level).

2.1.2. Incorporating energy-based intelligence

Achieving energy efficiency in manufacturing is insufficient when limited to: metering, monitoring, providing energy consumption records and audit trails and generating reports. While these capabilities improve energy awareness, they do not suggest ways to reduce energy consumption or incorporate reactive mechanisms. Significant improvements may require more sophisticated measurement, analysis and control techniques. For example, sophisticated methods can help to allocate resources optimally and to react toward expected or unexpected events. There is a growing body of optimization approaches, computational intelligence algorithms, forecasting and simulation models developed that are enhanced with the energy perspective (for examples see e.g., [15,24–27]). Less work appears to have been done regarding an emissions trading approach [28]. However, there remains a gap between the approaches available and the actual implementation within the ISs [2]. To reap the full potential of energy intelligence, manufacturing companies should embed such sophisticated models into their systems.

2.1.3. Interfaces with conventional enterprise systems

Achieving energy efficiency in manufacturing requires an energy-aware IS to complement with conventional enterprise systems (e.g., ERP, MES, APS or PDM[1]), since at the very least it must rely on such systems for the acquisition of manufacturing and production data. Let us illustrate this requirement through an indicative example: while an APS delivers information regarding a given detailed schedule, an energy-aware IS modifies the reference schedule to account for energy consumption without changing, per each individual job, the assignment to machines and the sequencing (i.e., the order in which the job visits the machines) but rather the order in which different jobs visit some particular machines; this modification must then be fetched back to the APS. Thus, the strong demand for giving special attention to the interfaces between the systems [2,12,17,19,30] highlights such interfaces as a key functionality within an energy-aware IS. A work of significant relevance is that of Liao [29] who presents possible interface paradigms in energy management systems and feasible ways of realizing such interfaces. These interfaces include the interactions with external systems and data sources as well as the interactions within the energy management system.

[1] Advanced Planning and Scheduling, Product Data Management.