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Sustainability in manufacturing operations scheduling: A state of the art review

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ABSTRACT

Sustainability in manufacturing systems is an urgent requirement for today's manufacturing companies. This paper focuses on sustainable manufacturing operations scheduling, a subject which has been attracting increasing interest from researchers in recent years. This paper presents a state of the art review of this field. First, it characterizes what can be considered as sustainable manufacturing operations scheduling, and introduces the relevant challenges and issues. An analysis of the literature is then proposed, and organized according to three keys. The shortcomings in the literature are then discussed in depth, and subsequently urgent problems that must be solved through research in order to meet industry requirements are pointed out.

1. Introduction

Sustainability in manufacturing systems is an increasingly important requirement for today's manufacturing companies due to several established and emerging causes: environmental concerns, diminishing non-renewable resources, stricter legislation and inflated energy costs, increasing consumer preference for environmentally friendly products, etc. Efforts to develop sustainable manufacturing systems must consider issues at all relevant levels (product, process, and system), and not just one or more of these in isolation. The specialized literature reports many studies at all these levels, but they are generally carried out at strategic levels: supply chain design, layout design, cleaner product and production mean design, construction, recycling process, etc. (see [1–5], for example). One of the main reasons for this emphasis on strategic levels is that the highest levels within organizations have driven much of the efforts toward sustainability. Nevertheless, it is important to point out that sustainability must urgently be taken into account at all levels, not only at the strategic one, but also at the tactic and operational levels to have a complete transmission belt from global policies to operational activities. The links among these different levels are then crucial to assure a correct treatment of sustainability issues in the whole manufacturing system.

In real production processes, scheduling is one of the key factors at the operational level that influence production efficiency, quality and cost. In addition, differences in scheduling will also have an effect on resource consumption (energy efficiency) and emissions (GHG, waste, scrap, etc.). According to [6], research on reducing environmental impacts through manufacturing operations control and scheduling was relatively limited prior to 2011. Early efforts on this subject were applied to the chemical industry [7]. Recently, increasing activity focusing on the operational level of manufacturing has been observed.

The present article focuses on two of the three pillars of sustainable development: environmental and economic (the social pillar is not addressed in this paper), and explores in depth a set of initial ideas exposed in [8]. It reviews the existing literature dealing with sustainable manufacturing operations scheduling in order to provide impetus for further research. For this purpose, challenges in sustainable manufacturing operations are characterized first. Different forms of sustainability in manufacturing operations scheduling are pointed out, and some illustrative contributions are presented. This paper then proposes a global typology to position the different contributions. From this, shortcomings in the literature are outlined, and some prospects that need to be urgently addressed to meet the challenges imposed by the need for sustainable manufacturing operations scheduling are presented.

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2. Sustainable manufacturing and sustainable manufacturing operations scheduling

The United Nations Brundtland Commission widely introduced the definition of sustainable development in 1987 [9]: "development which meets the needs of current generations without compromising the ability of future generations to meet their own needs".

In general, making development sustainable is a challenging and complex task involving many factors such as technology and engineering, economics, environment, health and welfare of people, social desires, and government strategies, procedures and policies. Sustainability can thus be viewed as having three pillars: environmental, economic and social (including political).

Regarding industrial processes, the main initiatives of the nations focused on restricting the adverse environmental impacts of energy consumption. Energy consumption directly impacts economic progress [10], and so the energy dilemma faces two major challenges. Countries must reduce the adverse environmental impact of energy consumption, but they also need to consume energy for industrialization. They can meet both challenges if they can improve the usable energy output-input ratio, i.e., "energy efficiency" [10]. In the past, the economic aspect of sustainability was the main focus, whereas corporations have recently started to address environmental sustainability. Despite this, environmental sustainability practices have been traditionally viewed as the voluntary responsibility of companies. Nowadays, in the light of stricter legislation, industrial standards, and rising energy costs, this perception is changing [11]. Hence, as it is pointed out in [12], companies are not only required to adopt a minimal environmental compliance strategy, but also to consider sustainability practices as a catalyst for innovation and competitiveness. This very complex and challenging undertaking must also consider issues at all relevant levels in manufacturing—product, process, and system [3]. Moreover, industrial challenges arising from the deregulation of the electricity markets and the increasing presence of unpredictable renewable energy sources must also be taken into account [13]. In [14] the authors present an analysis study in which the results confirm the positive impacts of the different programs adopted by companies (such as design to recycle, life cycle analysis, environmental certification, improve employees' working conditions or projects to support the external community) on each dimension of the triple bottom line of sustainability (environmental, social and economic performance).

Manufacturing systems are widely used industrial systems of which the operations can be seen as a discrete set to be scheduled and controlled [15]. Several notions are often used to describe strategies or philosophies that are more or less similar in the context of sustainability in manufacturing: lean[1], clean, green manufacturing to name a few. In [17], sustainable manufacturing refers to the set of technical and organizational solutions contributing to the development and implementation of innovative methods, practices and technologies in the field of manufacturing, to address worldwide resource shortages, to mitigate the excess environmental load, and to enable environmentally benign product life cycles. In order to focus on a given notion of sustainable manufacturing, the definition of sustainable manufacturing provided by the US Department of Commerce [18] was adopted in this paper: "the creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound".

As introduced, this paper focuses on sustainable manufacturing operations scheduling, taking two of the three pillars into consideration: environmental and economic. In this paper, manufacturing operations refer to low-level short-term or even real-time decisions applied to manufacturing systems. Upper levels such as mid-term production planning, supply chain, and business levels are not considered. Lower levels dealing with actuators/sensors and physical behavior are not considered either. Process monitoring, inventory and tool management, machine control, job/task scheduling and maintenance, to name a few, are typical functions relevant to this manufacturing operations level [19].

Manufacturing operations management, and especially scheduling in manufacturing, is one of the most studied problems by operations research and control communities. Scheduling is the allocation of resources (human and technical) to tasks over given time periods, and its goal is to optimize one criterion, or more [20]. In this paper, scheduling is taken in a broad sense, encompassing predictive approaches, dynamic/reactive approaches, and real-time control techniques.

In [8], the authors summarized the main challenges and trends in sustainable manufacturing operations scheduling, and identified three emerging challenges in the context of sustainable manufacturing operations. These challenges are summarized to show the importance of sustainable manufacturing operations scheduling in assisting the overall features of sustainability in manufacturing:

- One of the most important strategies to improve sustainability in manufacturing is to reduce the energy consumed during the manufacturing phase [3,21,22]. Manufacturing processes are energy intensive, making this stage a primary source of energy consumption and carbon footprint generation. The industrial sector currently accounts for about one half of the world's total energy consumption. In addition, it is estimated that machining processes account for about 5% of the GDP in the developed world [3]. Furthermore, the energy efficiency of machine tools is generally less than 30% [23], and combined with dynamic pricing and significant limitations on peak energy, detailed manufacturing scheduling and control systems will have a considerable effect on energy consumption and the associated cost. The manufacturing sector has made continuous progress toward energy efficiency. However, the economic benefits arising from energy efficiency have not been fully exploited [12]. Adopting energy management capabilities has enhanced many existing manufacturing enterprises. However, these capabilities are generally limited to energy monitoring, analysis, and reporting. There is still a need for energy-aware manufacturing in order to take energy efficiency into account when making decisions during manufacturing operations.
- A major risk of "unsustainability" stems from the operational levels of the manufacturing phase (pollution, waste, including energy wastage) [1]. Some processing industries such as chemical, food, refining, paint or metal industries, use a lot of energy, and present a high risk of generating significant quantities of waste or pollution. For these kinds of industry, research also focuses on waste management, leading in particular to cleaner production. Manufacturing and industrial processes are also known to be major sources of greenhouse gas (GHG) emissions. Statistics have shown that GHG emitted from the use of energy sources such as electricity, coal, oil, and gas during manufacturing accounts for more than 37%, even 50%, of the world's total GHG [24]. Therefore, businesses have begun taking steps to reduce GHG emissions from their products and services under mounting pressure stemming from the implementation of the Kyoto protocol and the Copenhagen protocol. Nevertheless, it is still difficult

[1] The relation among lean and green manufacturing have been often discussed. Both concepts display similarities at the level of resource productivity, organizational change, and source reduction. However, during implementation of the concepts some trade-off situations might appear. For an in-depth analysis see [16].

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