Sustainability in Manufacturing Operations Scheduling: Stakes, Approaches and Trends

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Abstract. In this paper it is explained how manufacturing operations scheduling can contribute to sustainability. For that purpose, the relevant stakes are first presented. Sustainable manufacturing operations are then characterized. Different forms of sustainability in manufacturing operations scheduling are pointed out and some illustrative contributions are positioned.

Keywords: Sustainability, manufacturing operations, scheduling, production control.

1 Introduction

Several recent literature reviews are available in sustainable manufacturing, but most of the time the studies are led at the strategic levels: supply chain design, layout design, cleaner product and production mean design, construction, recycling process, etc., see for example (Garetti and Taisch, 2012), (Gunasekaran and Spalanzani, 2012). One of the main reasons for the strategic level emphasis is that much of the sustainability efforts have been driven by highest levels within organizations. According to (Fang et al., 2011), research on reducing environmental impacts through manufacturing operations control and scheduling has been relatively limited. Early efforts in this direction were applied in the chemical industry (Grau et al., 1995). There has been relatively little effort on energy-aware scheduling of manufacturing operations (Bruzzone et al., 2012).

Despite this, this paper intends to explain how manufacturing operations can contribute to sustainability, and especially to two of the three pillars in sustainable development: the environmental and economical pillars (the social pillar is not addressed in this paper). The present article aims to review these two pillars at the detailed manufacturing operations level with the intent to provide impetus for further research. For that purpose, the relevant stakes are first presented. Sustainable manufacturing operations are then characterized. Different forms of sustainability in manufacturing operations are pointed out and some illustrative contributions are positioned.

2 Sustainable manufacturing operations: stakes and trends

Three emerging stakes can be identified in the context of sustainable manufacturing operations.

First, despite the fact that machining represents a small fraction of the whole product life cycle, reducing the energy consumed during this phase was recently identified as one of the most important strategies to improve sustainability in manufacturing (He et al., 2012), (Pusavec et al., 2010). This is driven by the fact that in the 2010's, the industrial sector accounts for about one-half of the world's total energy consumption. More, the consumption of energy by the sector has almost doubled over the last 60 years (Fang et al., 2011). (Garetti and Taisch, 2012) add that manufacturing is responsible of more than 33% of the global final energy consumption and 38% of direct and indirect CO2 emissions worldwide the remaining are attributed to the transport sector, households and services. Furthermore, energy efficiency of machine tools is generally less than 30% (Hu et al., 2012) combined with dynamic pricing and significant limitations on peak energy will make detailed manufacturing scheduling and control systems will have considerable influence on the energy consumption and associate cost.

Second, manufacturing has a huge impact on the environment and major risk of "unsustainability" comes from the operational levels of the manufacturing phase (pollution, waste, including waste of energy) (Garetti and Taisch, 2012). Some process industry such as chemical, food, refining, paint or metal industries are highly energy consuming and present a high risk to generate important amount of waste or pollution. For example, in (Chen et al., 2013) is pointed the fact that during 2000 about 60% of the $700 million energy expenditures in 37 U.S. automotive assembly plants are spent in painting processes. In such a context, a 5% reduction in energy consumption may result in a saving of more than half million dollars per year for each plant. Given the rapidly increasing energy prices during the past ten years, the saving would be even more remarkable in present days while a significant amount of savings could be achieved without any major equipment investment, focusing efforts on operations. Moreover, low margins in such industries make seeking for efficiency a strategic objective (Akkerman and van Donk, 2008). For these kinds of industry, research is also focused on waste management, leading especially to cleaner production. Manufacturing and industrial processes are also known to produce large amounts of C02 but it is difficult for enterprises to consider renewable sources application and emissions reduction when making manufacturing and operation decisions, especially on the production planning and scheduling problem (Wang et al., 2011).

Third, from an industrial point of view, with the successive financial and economic crises, more and more industrial managers face a new kind of problem: their manufacturing systems become oversized compared to the market need and they wonder if they could limit their energy consumption. For example, in (Yildirim and Mouzon, 2012) is related a study of a Wichita, KS, aircraft small-parts supplier, where it was observed that, on average, in an 8-h shift, 16% of the time, machines stand idle. During these idle periods, there is an opportunity to save at least 13% of the total energy consumption by simply turning them OFF when they are not processing any jobs. The problem may be obvious at a first glance, but some unexpected issues arise, such as:

memorization/retrieval of last information before shut-down, re-initialization of robots (programs, parameters and states), re-synchronization of manufacturing processes after restart, etc. (Pach et al., 2014).

Therefore even if the manufacturing operation is not a prime driver of sustainability, it is becoming increasingly important to study various ways in which manufacturing operations can contribute globally to sustainability. Prior work has led to an increasing awareness and interest in integrating sustainability considerations when designing manufacturing operations scheduling and control system as can be evidenced by several recent special issues of international journal, dealing with “automation in green manufacturing” (Li et al., 2013), “sustainable manufacturing” (Garetti et al., 2012) or “Recent cleaner production advances in process monitoring and optimisation” (Klemeš et al., 2012). These special issues addressed some aspects relevant to sustainability applied at detailed manufacturing operations and some of the papers published in these special issues are reviewed in this article. Moreover, previously released literature reviews have been realized on close topics. They focused for example on a specific kind of manufacturing systems, such as: mixed-models manufacturing processes (Neugebauer et al., 2012), specific usable tools, such as simulation software (Thiede et al., 2013), industrial-oriented software, such as manufacturing execution systems (Soplop et al., 2009), energy consumption reduction in manufacturing from a technology (Park et al., 2009) or from a processes and systems (Duflou et al., 2012) point of views. All these reviews contain of course some considerations paid to manufacturing operations scheduling and control, but partially.

3 When manufacturing operations scheduling is sustainable?

Several notions are often used to describe similar strategy or philosophy in the context of sustainability in manufacturing: lean, clean, green manufacturing to name a few. In this paper, **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 manufacturing field, for addressing the world-wide resources shortages, for mitigating the excess of environmental load and for enabling an environmentally benign life cycle of products (Garetti et al., 2012).

Manufacturing operations refer in this paper to the 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 in this paper, as well as lower levels dealing with actuators/sensors and physical behaviour are not considered either. We focus on process monitoring, inventory and tool management, machine control, scheduling and maintenance among the main functions of manufacturing operations (Trentesaux and Prabhu, 2013).

Manufacturing operations management in a broad sense, and especially scheduling in manufacturing, has been one of the most studied problems by the operation research and control communities, and this holds also true considering sustainability issues. **Scheduling** is the allocation of resources (human and technical) to tasks over given time periods and its goal is to optimize one or more (Pinedo, 2008). In this paper, scheduling is taken in a broad sense, encompassing predictive approaches, dynamic/reactive approaches and real-time control techniques.

The question that arises is then: *under which conditions a manufacturing operations scheduling method can be termed as sustainable*? From our point of view, the key point is related to the consideration of means in addition to classical time-based (completion times, flow times, tardiness/earliness…) or mixed time/quantity-based (throughput…) production objectives. In the context of sustainable manufacturing operations, two kinds of means can be identified: the **input means** that enable the realization of a scheduling (energy, machines, inventories, raw materials, tools…) and the **output means** that are consequences of the realization of the scheduling (waste, scrap, pollution). Due to its specificity, money is not present in the input means list in the sense that it is the driver of all the other input means. As a consequence, from our point of view, the answer is: *it is when a method considers in addition to usual production objectives (time-based or time/quantity-based) the optimization of input means and/or output means when computing/constructing these schedule*s.

This answer guided us to realize our literature review to determine if contributions are relevant or not to sustainability in manufacturing operations scheduling. Thus, in a sustainable context, input/output means have then to be considered as decision variables when computing schedules in a predictive or reactive manner. For example, energy and resources are such typical means and must be seen as tuning/decision parameters. Other approaches, typically for example the ones that consider energy as a fixed cost, which is not a value to reduce as much as possible, cannot be considered as contribution to sustainability. Typically, in such a context, if the energy consumption for a schedule is assumed to be constant, then it can be ignored (Yildirim and Mouzon, 2012). It is the same for the numerous contributions in the manufacturing scheduling domain that consider the quantity of available machines as a constraint, not a value to be reduced as much as possible. Typically, the literature review proposed by (Hoogeveen, 2005) is out of the scope since the author considered only time-related performance objectives, being mono or multicriteria-based: no attention was paid to input nor output means.

Other numerous works concern the solving a problem known as the resource-constraint scheduling problem (RCPSP) (Brucker et al., 1999). Roughly, a RCPSP problem is a project planning problem considering renewable resources (manpower, machines…) and nonrenewable resources (budget, energy) (Hartmann and Briskorn, 2010). Fundamentally, there exist two ways to optimize a RCPSP problem: either minimizing the project makespan subject to a fixed upper bound on the non-renewable resource (*the budget problem*), or at minimizing the total allocation subject to a given bound on the makespan (*the deadline problem*) (Brucker et al., 1999). A lot of extensions of this problem have been proposed (Hartmann and Briskorn, 2010). These works address high-levels in manufacturing system, which is beyond the scope of this paper. Even if these works are not directly related to sustainability, they have inspired numerous studies related to predictive manufacturing operations scheduling considering sustainability.

More precisely, considering input/output means in scheduling enlarges the debate and leads to the consideration of a new performance indicator, *efficiency*, in addition to the classical *effectiveness* one: seeking for the best use of means refers to efficiency while seeking for the best results, effectiveness (Roghanian et al., 2012). Efficiency and effectiveness are commonly performances indicators used in economy, accounting, business and management. Roughly speaking, efficiency is often assimilated as "doing things right" while effectiveness, "doing the right things" (Roghanian et al., 2012). The ideal sustainable manufacturing scheduling system realizes everything (maximum effectiveness) using nothing (minimum use of means, that is maximum efficiency). In reality, effectiveness and efficiency are conflicting objectives: for example, reducing energy consumption may imply a loss of performances in operations (makespan).

4 Illustrative works in sustainable manufacturing operations

To illustrate the previous discussion, some contributions from the literature are positioned in this part. This positioning is made according to the addressed means in the sustainable-oriented scheduling models (input, output or mixed). Obviously, the aim is not to provide a complete review.

4.1 Input oriented approaches: energy, inventory, machine, tools

Input-oriented scheduling approaches are the most often developed. For this approach, optimal predictive scheduling are mainly proposed. A first type of predictive approach works is focused on the elaboration of a trade-off between effectiveness and input-means oriented efficiency. It has been widely addressed in the literature. It consists in minimizing input resource consumption while maintaining the quality of the schedule as a compromise, aggregation being made using a mono or a multi-criteria aggregation method, see for example (He et al., 2012), (Zhang et al., 2012), (Vergnano et al., 2010) or (Newman et al., 2012). Most of these approaches are statically handled, but this tradeoff can be realized in real time, in an opportunistic manner, using for example potential fields (Pach et al., 2014). In a second type, less addressed but promising and innovative, the approach consists in optimizing scheduling effectiveness under input means profile as hard constraints (eg., expressed in terms of money or maximum available power for given time windows, typically in the smart grid, or more simply, a maximum peak power value to be respected). This could lead for example to scheduling mechanisms shortening the makespan if more energy is available while increasing the makespan if less energy is available, see for example (Pechmann et al., 2012), (Bruzzone et al., 2012) or (Artigues et al., 2013). In the last type, the scheduling effectiveness is maintained as the main objective, while the input resource use/consumption is minimized, if possible, see for example (Mashaei and Lennartson, 2013) or (Chen et al., 2013).

Approximate predictive approaches are also proposed (Santos and Dourado, 1999), (Yildirim and Mouzon, 2012) as well as simulation/optimization ones (Weinert et al., 2011), (Prabhu and Taisch, 2012).

4.2 Output oriented approaches: waste, pollution, scrap, greenhouse gases

These approaches are less studied, but some contributions are among the first ones in the field. Especially, chemical plants constitute a classical and historical application field of environment considerations in production operations. For example, (Grau et al., 1995), (Vaklieva-Bancheva and Kirilova, 2010) and (Adonyi et al., 2008) proposed optimal predictive approaches in the context of waste and cleanness management.

4.3 Mixed approaches

Some mixed approaches, considering simultaneously input and output means have been developed. For example, (Fang et al., 2011), (Wang et al., 2011) considered simultaneously energy and carbon footprint. From our review, mixed approaches are then not well developed as for output oriented approaches.

5 Conclusion and future trends

In this article, the role of scheduling manufacturing operations in a sustainable context was addressed. The research activity is growing but still does not fill the gap between research and industrial needs. Input-oriented approaches are the most studied ones but the field is still nascent (most of the references are after 2012). Output-oriented and mixed approaches are clearly unstudied. Given the future evolutions, scheduling under sustainability constraints should be urgently addressed. From our point of view, future trends concern the development of "means-friendly" systems, being manufacturing execution systems or scheduling systems. This concerns typically: the integration of opportunistic behavior in energy savings, the optimization of greenhouse gases emission in scheduling, and more globally the definition of scheduling benchmarks integrating output means considerations. From our review, it is indeed clear that output and mixed approaches should also be urgently addressed. Innovative approaches and concepts such as cyber-physical systems, intelligent products, product-service systems to name a few can bring some insights to contribute to the development of effective and efficient sustainable scheduling systems. This paper did not considered the social pillar which should be studied to complete the view on the addressed issue.

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