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Green scheduling of a two-machine flowshop: Trade-off between makespan and energy consumption

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ABSTRACT

Sustainability considerations in manufacturing scheduling, which is traditionally influenced by service oriented performance metrics, have rarely been adopted in the literature. This paper aims to address this gap by incorporating energy consumption as an explicit criterion in shop floor scheduling. Leveraging the variable speed of machining operations leading to different energy consumption levels, we explore the potential for energy saving in manufacturing. We analyze the trade-off between minimizing makespan, a measure of service level and total energy consumption, an indicator for environmental sustainability of a two-machine sequence dependent permutation flowshop. We develop a mixed integer linear multi-objective optimization model to find the Pareto frontier comprised of makespan and total energy consumption. To cope with combinatorial complexity, we also develop a constructive heuristic for fast trade-off analysis between makespan and energy consumption. We define lower bounds for the two objectives under some non-restrictive conditions and compare the performance of the constructive heuristic with CPLEX through design of experiments. The lower bounds that we develop are valid under realistic assumptions since they are conditional on speed factors. The Pareto frontier includes solutions ranging from expedited, energy intensive schedules to prolonged, energy efficient schedules. It can serve as a visual aid for production and sales planners to consider energy consumption explicitly in making quick decisions while negotiating with customers on due dates. We provide managerial insights by analyzing the areas along the Pareto frontier where energy saving can be justified at the expense of reduced service level and vice versa.

1. Introduction

Scarcity and likely future shortages of key materials and energy resources used in modern manufacturing have come into the focus of public interest. This challenge necessitates resource-efficient engineering, as the transition from a linear to a circular economy has already begun (Sun, 2013). We need innovative resource-efficient and low-carbon economy solutions for conserving resources, maximizing recovery of materials, reusing, and recycling as well as minimizing waste to respond to and pro-actively prepare for significant scientific and technological challenges of sustainable manufacturing. Manufacturers feel the pressures of public awareness of sustainability, increasing energy costs, and growing energy security concerns. Therefore a new line of research has been rapidly developing for the reduction of energy and power consumption in manufacturing without compromising service levels.

Sustainable manufacturing is substantiated by concepts such as conservation of energy, material and value added products, waste prevention and environment protection. The manufacturing industry as a whole uses massive amounts of energy and contributes to 36% of global CO_2 emissions (OECD-IEA, 2007). In the UK, industry's energy consumption accounts for 16% of the total consumption (MacLeay, Harris, & Annut, 2014). This is equivalent to 194 million metric tonnes of CO_2. To put this figure into perspective, it corresponds to greenhouse gas emissions from 451 million barrels of oil (EPA 2013). Moreover, according to the Department of Energy & Climate Change (DECC), the total demand for energy in the UK was slightly above the total supply in 2012 (DECC, 2013), which resulted in importing energy to satisfy the demand. Although the current oil prices suggest an abundance of resources for energy, the increasing trend in population, energy consumption and wastage of energy puts the world at risk of facing an energy crisis in the near future as is evidenced by the European Union's developing contingency plans

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against any kind of energy supply outage (Reuters, 2015). This is why manufacturing companies are obliged to not only make efforts to reduce their environmental impact but also to proactively consider likely energy shortages in their operations. One way to do this is by using highly effective ways of reducing their electrical energy consumption (Duflou et al., 2012). Examples of such ways include selectively shutting down machines during idle time (Mouzon & Yildirim, 2008; Mouzon, Yildirim, & Twomey, 2007) where feasible or operating them at speeds allowed by the set service level targets.

Our research is novel in its integration of energy considerations into the shop floor scheduling. We leverage variable processing times with different energy consumptions to analyze the trade-off between makespan and energy consumption in a two-machine sequence dependent flowshop scheduling problem. Our research is inspired in part by similar trade-offs between speed and fuel emissions in vehicle routing (Demir, Bektaş, & Laporte, 2014; Jabali, Woensel, & de Kok, 2012) and maritime transportation (Psaraftis & Kontovas, 2013; Qi & Song, 2012). We argue that in flowshop manufacturing, there is a trade-off between optimizing makespan (which is dependent on processing and setup times) and energy consumption. Therefore, analyzing the trade-offs in an efficient way can support decision making when scheduling manufacturing operations in this setting. To the best of our knowledge, this problem has not been addressed in the extant literature. This paper aims to close this gap in an attempt to promote the notion of green scheduling in manufacturing.

In this paper we address the trade-off between energy consumption and service level in shop floor manufacturing. We develop a mathematical model to minimize makespan, a measure of service level and total energy consumption, an indicator of environmental sustainability in a two-machine permutation flowshop scheduling problem that is characterized by sequence dependent setups. Two-machine flowshop scheduling problems have many real world applications including metalworking (Uruk, Gultekin, & Akturk, 2013), printed circuit board (PCB) manufacturing (Sabouni & Logendran, 2013) and shampoo industry (Belaid, T'kindt, & Esswein, 2012) among others. As a result, two-machine scheduling problems have attracted significant attention from practitioners and researchers. From the 1950s when Johnson developed one of the first algorithms for two-machine flowshop scheduling (Johnson, 1954), the problem has been widely studied in the literature from different perspectives. A recent search on Scopus[1] using the keywords "scheduling OR sequencing" AND "flowhsop OR 'flow shop' " AND "two-machine" found more than 630 articles. More interestingly, we observed that more than 50% of these research papers have been published in the last 10 years, which shows a growing attention to this problem in recent years. These types of problems are observed in industrial applications (e.g. metal processing, brake manufacturing and electronics), finance, information processing, health care, cosmetics, and satellite imaging, where it is essential to explicitly consider the setup times in scheduling the production/service systems because of their significant impact on operational costs (Gharbi, Ladhari, Msakni, & Serairi, 2013). Scheduling problems with sequence-dependent setups have attracted attention from many researchers due to their importance to industry and because of the challenges they present to solution methodologies (Zhu & Wilhelm, 2006). Examples of sequence-dependent scheduling problems can be found in metalworking (Baghaei, 2013), furniture manufacturing (Agnetis, Detti, Meloni, & Pacciarelli, 2001) and paint shops (Mansouri, 2005).

Energy consumed during manufacturing depends on power, processing time, and machine-specific properties such as operating speed. The transition to more energy-efficient processes will require substantial investment and a change of mindset. If the ideas presented in this paper are taken up by the scheduling practitioners in the manufacturing sector, it will be possible to make decisions including both service level and environmental considerations in sectors such as electronics (Trovinger & Bohn, 2005), paper (Pinedo, 2012) and textiles (Clark, Almada-Lobo, & Almeder, 2011). An aspect of these ideas that may be appealing to scheduling practitioners is that they are process-oriented; they do not require huge investments in machine redesign or product redesign, which may be very difficult for small and medium-sized enterprises. Considering the high pressure on the environment from fossil-based energy sources, reducing energy consumption on the shop floor is attractive to manufacturers not only environmentally but also economically as well. That is why an increasing number of scientists are working on saving energy and reducing carbon emissions in manufacturing operations (Liu, Zhang, Yang, Chen, & Huang, 2013). The contributions of this paper can be summarized as follows:

- introducing the concept of green scheduling as a new approach to shop floor scheduling;
- developing a novel multi-objective mathematical model, taking into account energy consumption as an explicit decision criterion by leveraging variable processing times;
- defining lower bounds on total energy consumption and makespan for benchmarking;
- developing a new heuristic algorithm to find a good approximation of Pareto optimal solutions in a short amount of time;
- validating the performance of the heuristic algorithm through comprehensive experiments and benchmarking with CPLEX based on three performance metrics: accuracy, diversity and cardinality of the Pareto frontiers;
- providing the managerial implications of green scheduling for production planners and sales managers of manufacturing companies.

The remainder of the paper is organized as follows. Section 2 reviews the relevant literature. Section 3 develops the mathematical model and the lower bounds for the two objectives. The constructive heuristic is described in Section 4. The experimental setup is presented in Section 5, followed by the presentation and discussion of results in Section 6. Finally, Section 7 concludes the paper and identifies future research directions.

2. Literature review

Energy consumption and carbon footprint have rarely been considered explicitly in the literature on shop floor scheduling. There have been a few conceptual research papers in recent past in an attempt to incorporate such metrics with conventional performance indicators for shop floor manufacturing (e.g. makespan, total tardiness, mean lateness, combined earliness-tardiness and total flow time in Mokotoff, 2010). Recently, Zhang, Zhao, Fang, and Sutherland (2014) considered energy cost and carbon footprint under varying energy price based on the time of use. The traditional scheduling literature assumes fixed processing times for operations with some exceptions in parallel and hybrid flowshop scheduling problems (e.g. Behnamian & Fatemi Ghomi, 2011). However, Ding, Song, and Wu (2015) considered variable processing speeds in a permutation flowshop scheduling problem. It is therefore realistic to assume variable machine speeds since Ahilan, Kumanan, Sivakumaran, and Dhas (2013) showed that the processing time and energy consumption of CNC machines can vary significantly by changing cutting speed, feed rate, depth of cut and nose radius. As a result, relaxing the assumption of fixed processing time provides the opportunity to save energy by extending processing times or to improve customer service level by shortening processing times.

Our study brings together two lines of literature: sustainable manufacturing and multi-criteria decision making. Within the sustainable manufacturing literature, we focus on energy considerations in

[1] Conducted on 27 July 2015.