Journal of Cleaner Production 102 (2015) 418–427

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Reducing environmental impact of production during a Rolling Blackout policy – A multi-objective schedule optimisation approach

Ying Liu [a,*], Haibo Dong [b], Niels Lohse [c], Sanja Petrovic [d]

[a] School of Aerospace, Transportation and Manufacturing, Cranfield University, Cranfield, MK43 0AL, United Kingdom
[b] Division of Engineering, University of Nottingham Ningbo China, Ningbo, 315100, China
[c] Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, Loughborough, LE11 3QZ, United Kingdom
[d] Business School, University of Nottingham, Nottingham, NG8 1BB, United Kingdom

A R T I C L E I N F O

Article history:
Received 20 December 2014
Received in revised form
3 April 2015
Accepted 12 April 2015
Available online 24 April 2015

Keywords:
Energy efficient production planning
Sustainable manufacturing
Job shop scheduling

A B S T R A C T

Many manufacturing companies in China currently are suffering from a Rolling Blackout policy for the industry electricity supply which means that the government electricity is cut off several days in every week resulting in manufacturing companies illegally starting their own diesel generators to maintain production. However, the private generation of electricity is more polluting and costly than the government supplied resource. Thus, the increased price of energy and the requirement to become more environmentally sustainable exert substantial pressures on manufacturing enterprises to reduce energy consumption for cost saving and to become more environmentally friendly. Scheduling of less energy consumption critical operations during Rolling Blackout periods can help minimise the negative effect of this policy. This is a multi-objective optimisation problem as production due dates cannot be ignored and cost is not directly proportional to electricity consumption anymore. Optimal scheduling even of relatively small production orders is clearly beyond the capability of manual tools or common single objective scheduling optimisation methods. Therefore, a multi-objective scheduling optimisation method has been developed which includes reducing electricity consumption and its related cost as part of the objectives in addition to total weighted tardiness. This research focuses on classical job shop environments which are widely used in the manufacturing industry in China and the rest of the world. A mathematical model for the tri-objectives problem that minimises total electricity cost, total electricity consumption and total weighted tardiness has been developed. A specific heuristic has been devised for investigating how the Rolling Blackout policy affects the performance of existing scheduling plans. This heuristic can also be used as a remedial measurement by plant managers if they do not have access to multi-objective optimisation tools. The Non-dominant Sorting Genetic Algorithm has been used as the basis for solving the optimisation problem. Case studies based on four modified job shop instances have been studied to show the effectiveness of the proposed heuristic and the algorithm.

1. Introduction

The manufacturing industry is one of the most important energy consumers and carbon emitters in the world. For instance, every year in China, manufacturing consumes around 50% of the entire electricity produced (Tang et al., 2006), and generates at least 26% of the total carbon dioxide emissions. In order to reduce the carbon emission and balance the time-based unevenness of electricity demand, a Rolling Blackout policy is promulgated to industry electricity supply in some areas of China. This means the government electricity is cut off several days in every week for a specific company. This policy creates huge difficulties to manufacturing companies since their production can be significantly limited by the resulting lack of electricity to power their production machines. For some companies, up to 1/3 of their production capacity can be lost. To recover their production capacity, some companies illegally start their own diesel generators. This increases their electricity costs as the cost of this privately generated electricity is twice as high as the government supplied resource. The original intention of implementing the Rolling Blackout policy is to reduce emissions. Ironically, it results in the wide generation of private electricity which is more emission intensive. Based on the above discussion and the background of increasing price of energy (Kilian, 2008), a new objective for many

* Corresponding author. Tel.: +44 (0)7400028806.
E-mail address: ying.liu01@cranfield.ac.uk (Y. Liu).

http://dx.doi.org/10.1016/j.jclepro.2015.04.038

manufacturing companies in China is to reduce electricity consumption and cost during production as well as ensure quality and customer satisfaction when the Rolling Blackout policy is implemented.

The challenge they face is that as a result of the Rolling Blackout policy, minimising electricity consumption and cost while maintaining their order due dates, has become a none trivial triple objective optimal scheduling problem. Finding even close to optimal solutions is much beyond the capability of commonly used single objective methods which only consider the time domain. Furthermore, specific heuristics to consider the implications of the Rolling Blackout during scheduling have not yet been investigated. Hence, there is a clear need to first of all understand the potential of applying operational research methods to solve this problem. Secondly, simple heuristics should be defined to aid practitioners with improving the optimality of their schedules even without lengthy multi-objective optimisation which is often beyond the capabilities and skill sets of average small to medium sized companies.

Previous research by (Mouzon and Yildirim, 2008; Shrouf et al., 2014) confirm that operational research methods are providing an effective approach to reduce the energy consumption and its related cost to manufacturing companies by improving their production schedules. This is especially true in the mass production environments as production schedules are less complex yet any improvement can have a large effect due to large production volumes (Gutowski et al., 2005). Job shop type manufacturing environment are far more common but also inherently more complex due to larger product variety and diversity resulting in more complex material handling requirements. Consequently, optimising schedules for such environments is more challenging especially if multiple objectives need to be considered.

A very large number of small to medium sized companies in China operate a job shop production environment. Hence, the job shop has been selected as focus of this research. A general model of the tri-objective job shop scheduling problem that consider minimising total electricity cost (TEC), total non-processing electricity consumption (NPE) and total weighted tardiness (TWT) when the Rolling Blackout policy is applied (Electricity Consumption, Electricity Cost and Tardiness-EC2T) has been proposed in this paper for the first time. To solve this problem, the influence that the Rolling Blackout policy exerts on the existing scheduling plans of manufacturing companies needs to be understood first. To achieve this, a new heuristic has been developed to adjust existing scheduling plans to fit the government electricity supply time frame when the Rolling Blackout policy has been applied. This heuristic can also be used as a remedial measure for plant managers which enable them to minimise their TWT deterioration. A comparison between the adjusted and original schedules can demonstrate the policy's influence on TWT. In the adjustment scenario, the use of private electricity is forbidden to illustrate the worst case effect on schedules. Comparatively, the other solution for the manufacturing companies is to use the private electricity to maintain the existing scheduling plans when the policy is applied. It can be expected that the electricity cost will increase in this scenario since the private resource is more expensive. Based on the aforementioned two scenarios, it can be expected that, at least one of the schedule's performance indicator will be adversely affected (TWT or TEC), whether private electricity is used or not during the government electricity unavailable periods. This is the motivation for developing compromised scheduling plans to realise the trade-off between TWT and TEC. To solve this problem, the Non-dominant Sorting Genetic Algorithm (NSGA-II) (Deb et al., 2002) has been adapted for achieving the tri-objective optimisation of the EC2T problem with new encoding method for the first time.

In the remainder of the paper, following the background and research motivation in Section 2, the mathematical model of the EC2T is presented in Section 3. Then the procedure of the developed adjustment heuristic is presented in Section 4. A scheduling plan comparison experiment is presented in this section to investigate the influence that the Rolling Blackout policy exerts on existing schedules. In Section 5, a new encoding schema as well as crossover and mutation operators are provided to solve the EC2T and a case study is presented to demonstrate the effectiveness of the algorithm for the research problem.

2. Background and motivation

The amount of reported research in the area of scheduling with environmentally-oriented objectives is currently small but increasing. The most relevant studies were conducted by Mouzon (2008) and He et al. (2012). Based on their work and the approach developed by Kordonowy (2003) which individually considers the total energy used by each stage of machining processes, Liu et al. (2014) have further divided the electricity consumption of each machine tool into two components: the non-processing electricity consumption (NPE) and processing electricity consumption (PE) for scheduling optimisation. NPE is associated with machine start-up, shut-down and idling. The electricity consumed when a job is processed on a specific machine can be defined as job related processing electricity consumption (JPE), including the basic power consumption of machine tools, i.e. idle power, the runtime operations and the actual cutting consumption. Thus, PE is the sum of all the JPE on a specific machine. The JPE for the processing of each job can be considered to be a constant in a given manufacturing system provided that there are only single or the same type of machines for each operation. In this case, it has been proved by Liu et al. (2014) that by adjusting scheduling plans in a basic job shop only the total NPE can be reduced.

Based on the above, the current electricity saving methods (ESMs) at the manufacturing system level include: Sequencing, Turn Off/Turn On and Process Route Selection (PRS). The Sequencing method reduces the non-processing time of the machines in the system by changing the order of jobs on a machine. This reduces the idle electricity consumption of the system. The Turn Off/Turn On method (Mouzon, 2008) looks for opportunities to save electricity by turning off a machine tool when it becomes idle for a sufficient period of time. The Sequencing and Turn Off/Turn On can be applied to any type of manufacturing system to reduce the NPE provided that the start-up and shut-down times and energy requirements of the machines do not exceed the opportunities for saving. Comparatively, PRS is only applicable to workshops with alternative routes. It can reduce both PE and NPE by choosing different processing routes for job. Its ineffectiveness in workshops without alternative routes or having identical alternative routes for jobs, for instance, the job shop environment limits its range of application. Dispatching rules, a genetic algorithm and a greedy randomised adaptive search procedure have been proposed by Mouzon et al. (2007) and Mouzon (2008) to optimally use the aforementioned three methods to reduce both total NPE and PE for single machine and parallel machine environments. He et al. (2012) used PRS to decrease both total PE and total NPE for a flexible job shop environment. In addition, Bruzzonea et al. (2012) developed a method to modify the schedule of the jobs in flexible flow shops in order to adjust to the maximum peak power constraint. Subaï et al. (2006) consider energy and waste reduction in hoist scheduling problem of the surface treatment processes without changing the original productivity. Research considering the electricity price pattern as constraint, thereby achieving the cost saving is scarce. Herrmann and Thiede (2009) considered the use of operational