Energy-Efficient Resource Scheduling of a Single Resource with Production Requirements: A Joint Simulation and Scenario-Based Mathematical Programming Approach

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Improving energy efficiency in manufacturing yields significant cost and environmental benefits. Advanced data collection and execution technologies allow the implementation of data-driven dynamic control policies that turn on and off resources depending on the real-time data to save energy. Motivated by an automotive producer's paint oven on-off scheduling, we consider a single resource that operates in on, off and warmup modes. When the resource is on, it can be turned off immediately. However, when the turned-off resource is turned on, there is a delay for warm-up. The energy consumption in the off mode is the lowest. We present a scenario-based mathematical programming formulation to determine the optimal on-off schedule of a single resource that minimizes the average energy and early/late production costs while meeting the production requirements. We employ a cutting plane algorithm to solve this problem. We discuss using the scenario-based formulation with the random arrival times generated by a detailed digital twin of the production system feeding the resource.

Key words: Optimal production and energy control; Energy Efficiency; Resource scheduling

1. Introduction

The global push for decreasing green-house gas emissions to limit its effect on climate change has motivated manufacturers to focus on decreasing their energy consumption since a considerable portion of energy consumption globally can be attributed to manufacturing (Wang et al. 2017). From the energy consumed in manufacturing, a large portion is used in heating processes (Yan and Zheng 2020).

The contributions of this work are introducing a mathematical programming formulation for scheduling the on/off cycles for an energy intensive operation in order to decrease energy consumption while full-filling production requirements and giving a cutting plane algorithm that uses a scenario clustering approach to solve the problem in efficient time.

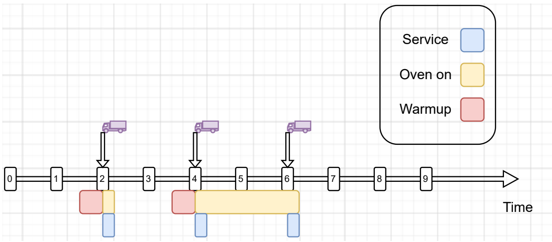

Figure 1. An example schedule that uses two cycles. In this case, the vehicles are admitted to the oven and their service starts as soon as they arrive in the system

2. Problem Definition

The setting of our problem is based on the problem of controlling the energy consumption in a major automotive manufacturing plant in Turkey. The energy consumption in the paint ovens constitutes a large portion of the production cost of the vehicles and an even larger portion of the total energy consumption in the plant. The ovens are among the last stages in the manufacturing process, and for this reason, any planned turning off of these resources can resulting in blocking upstream. The vehicles are categorized into vehicles with regular colors and special colors. The throughput for the regular color vehicles is high enough that any planned turning off of ovens cannot be done without compromising on the throughput. However, the utilization for the special color vehicles is lower, providing the opportunity for planned turning off of the ovens.

We consider a single resource that operates in different modes: on, off, and warmup. When the resource is on, it can be turned off immediately. However, a warmup is initiated when the turned-off resource is turned on. The warmup delay is deterministic and given as t^{WU}. The energy consumption in the off mode is the lowest and is set as 0. The energy consumption in the warmup mode c_{WU} can be higher than in the on mode c_{ON}. An on-off cycle is determined by the time the resource is turned on U_c and then turned off W_c for cycle c. An on-off schedule (U_c, W_c), $c = 1, \dots, C$ is a collection of on-off cycles during the planning horizon.

The jobs arrive randomly at the resource at different times. The arrival times A_j for J jobs are given. There is a requirement for the number of jobs that must be completed

The problem we consider is determining an on-off schedule for the planning horizon to minimize the total average energy and waiting cost, TC. Figure 1 depicts a sample on-off schedule that uses two cycles in the planning horizon. We incorporate stochasticity in the arrival time of the parts to the system through solving the problem for multiple scenarios simultaneously. To improve the time performance of this mathematical programming formulation, we use a cutting plane algorithm that adds constraints related to preventing production when the oven is off iteratively.

$$\min \quad \text{TC} = c_{WU} \sum_{c \in \mathbb{C}} (V_c - U_c) + c_{ON} \sum_{c=1}^{C} (W_c - V_c) + c_{WT} \sum_{j \in \mathbb{J}} (S_j - A_j) \tag{1a}$$

$$\text{s.t.} \quad U_c \geq 0, \qquad c \in \mathbb{C}, \tag{1b}$$

$$V_c - U_c \geq t^{WU} Z_c, \qquad c \in \mathbb{C}, \tag{1c}$$

$$
\begin{aligned}
&W_c \geq V_c && c \in \mathbb{C}, \quad (1d)\\
&S_j \geq V_c - M(1 - X_{cj}), && j \in \mathbb{J}, c \in \mathbb{C}, \quad (1e)\\
&S_j \geq A_j, && j \in \mathbb{J}, \quad (1f)\\
&F_j = S_j + t_j^{OT}, && j \in \mathbb{J}, \quad (1g)\\
&S_{j+1} \geq F_j, && j \in \mathbb{J}, \quad (1h)\\
&W_c \geq F_j - M(1 - X_{cj}), && j \in \mathbb{J}, c \in \mathbb{C}, \quad (1i)\\
&W_c \leq T_s, && c \in \mathbb{C} \quad (1j)\\
&U_{c+1} \geq W_c, && c \in \mathbb{C}, \quad (1k)\\
&Z_c \leq \sum_j X_{cj}, && c \in \mathbb{C}, \quad (1l)\\
&\sum_j X_{cj} \leq M Z_c, && c \in \mathbb{C}, \quad (1m)\\
&\sum_c X_{cj} = 1, && j \in \mathbb{J}, \quad (1n)\\
&X_{cj}, Z_c \in \{0, 1\}, && j \in \mathbb{J}, c \in \mathbb{C}, \quad (1o)
\end{aligned}
$$

For settings similar to the problem here, threshold-type policies have been shown to perform well (Tan et al. 2023).We use a threshold-type policy as a benchmark. The threshold policy utilizes two thresholds, one for turning the oven off when there are few vehicles to process and one for turning the oven on when many vehicles are waiting to be processed. For the purpose of assessing the performance of these methods we use a simulation model of the system that captures the dynamics of the vehicles in multiple upstream locations. Given the location of each vehicle in the system and the traffic of vehicles in front of it, the arrival time of the vehicle to the oven can be estimated and the mathematical programming framework works based on those estimates.

3. Results

In this work, we devise a mathematical programming formulation that generates the optimal schedule for controlling an energy-intensive operation in order to minimize energy consumption subject to stochasticity in part arrivals and production rate constraints. We have conducted numerical experiments that show the cutting plane algorithm can effectively reduces the solution time for the problem when multiple scenarios are considered.

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