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Designing energy-efficient serial production lines: The unpaced synchronous line-balancing problem

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A R T I C L E I N F O

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A B S T R A C T

One of the primary elements of a sustainable manufacturing initiative is that of energy efficiency. Line balancing can be used to design efficient manufacturing systems for paced assembly lines when the operation times are known, but may provide inefficient assignments with variable task times. Thus, we propose the use of unpaced synchronous lines as an alternative to paced lines when there is considerable variability in task times. While a great deal of research has been conducted on the line-balancing problem for paced synchronous production lines as well as for unpaced asynchronous lines, relatively little has focused on the unpaced synchronous configuration, despite its practical relevance. This research addresses this type of production line, with stochastic task completion times, by formulating an appropriate model and developing and evaluating a variety of solution methodologies utilizing extreme value theory as well as simulation. Computational results are presented to gain insight into the design and operation of unpaced synchronous systems.

1. Introduction

Research concerning the design and operation of production facilities has historically been from a productivity perspective. Recently, though, a focus on the environmental effects of manufacturing processes has induced firms to undertake sustainable manufacturing initiatives. The International Trade Administration (2014) of the U. S. Department of Commerce defines sustainable manufacturing "as the creation of manufactured products that use processes that minimize negative environmental impacts, *conserve energy* [emphasis added] and natural resources, are safe for employees, communities, and consumers and are economically sound."

Since energy conservation is "a crucial issue for sustainable development" (Hu & Kao, 2007), this research is concerned with the energy efficiency of production processes, in particular, the design of serial production lines. This is particularly appropriate as the "control of production operations is often regarded as one of the most cost-effective ways to improve energy efficiency in manufacturing" (Chen & Zhang, 2013). Furthermore, Bunse et al. (2011) stated that "companies that improve their energy efficiency and consequently their carbon footprint can improve their position to face challenges and costs resulting from current and future CO_2 regulations." The International Organization for Standardization (2014) is referencing the ISO 50001 standards on energy management systems are "intended to lead to reductions in greenhouse gas emissions and other related environmental impacts and energy cost through systematic management of energy."

The design of serial production lines can impact energy efficiency in two ways. First, the size of the facility is a primary determinant of energy use. As noted by Despeisse, Oates, and Ball (2013), "for some manufacturing industries (e.g., manufacture of motor vehicles, electrical machinery, radios, medical equipment), building related energy (i.e., space heating and lighting) contributes to approximately 40–60 percent of the overall energy consumed." Kawahara et al. (1997) have indicated that a reduction in the size of production systems has a considerable impact on the consumption of environmental energy, "owing to the decrease of spaces for illumination and air-conditioning, and the number of the operators." Specifically, they noted when the production equipment is reduced by 50 percent, the total energy saving in typical factories could be reduced from 18 percent (household electric appliance manufacturing) to as much as 71 percent (watch manufacturing). Therefore, designing energy-efficient production lines would call for the fewest possible number of operators/workstations necessary to meet demand as well as minimizing the resultant space requirements.

A second manner in which energy use is affected by the design of serial production lines has to do with productive vs. idle time. Chen and Zhang (2013) have indicated that "the simplest way to reduce energy consumption in manufacturing systems is to shorten the running time of machines." And Smith and Ball (2012) noted that "machining centers consume large amounts of electricity whether they

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are in operational model (metal cutting) or idle mode (waiting)." Yuan, Zhai, and Dornfeld (2012) modeled energy consumption as a direct function of the operating efficiency and operating time of a facility. So the appropriate assignment/scheduling of work to minimize idle time would also be effective in reducing a firm's energy use.

The traditional method of designing serial production lines has been the balancing of paced synchronous lines. Suwannarongsri, Bunnag, and Klinbun (2014) provided a line-balancing problem for an automobile factory in Thailand and illustrated how the "total energy per product and supporting energy per product can be decreased when cycle time is reduced." Fysikopoulos, Anagnostakis, Salonitis, and Chryssolouris (2012) conducted an empirical study of the energy consumption of an automotive assembly line and concluded that, with proper line balancing and planning, idle time can be eliminated and bottlenecks can be identified, saving energy and reducing costs. Since the idle time per unit of output is simply equal to the number of workstations multiplied by the cycle time less the sum of the task times, a reduction of one workstation—holding the demand (cycle time) and task times constant—would result in a decrease of idle time equivalent to that of the cycle time for every unit produced. Thus, line balancing can be an effective tool in sustainable manufacturing by minimizing the number of operators/workstations which, in turn, reduces the necessary space requirements and idle time.

The effectiveness of line-balancing procedures, however, is compromised when the task times are not known with certainty. Accounting for the resultant variability requires the assignment of fewer tasks within each workstation—and, therefore, additional workstations—to ensure that the work can be completed with a given (say, 95 percent) probability. This, in turn, causes the expected idle time to increase considerably within the workstations. Even fully-loaded workstations will incur idle time on 95 percent of the units. Obviously, this is contrary to the energy reduction initiatives of sustainable manufacturing. Therefore, we propose the utilization of *unpaced* synchronous production lines as an alternative to paced lines when there is considerable variability in task times. We will show that unpaced lines generally provide more efficient—thus, more energy-efficient—production processes than their paced counterparts.

In the next section, we discuss the research literature on serial production lines. We then define the problem in Section 3 and formulate an appropriate model. In Section 4, a construction heuristic is developed to solve the line-balancing problem. Extreme value theory is applied to the specific problem with normally-distributed task times; simulation is then proposed as a more general approach. Computational results concerning the effectiveness of the proposed heuristic are also presented in this section. In Section 5, analyses concerning the general performance of unpaced synchronous lines are described. Finally, we conclude the paper and present areas of future research.

2. Serial production lines

Buzacott and Shanthikumar (1993) have classified serial production lines by the manner of job movement between stations; that is, the lines can be asynchronous or synchronous (indexing). In asynchronous lines, the timing of the job movement between stations is not coordinated. As soon as a job is completed in a station, it is moved to the next station if it is not blocked (i.e., there is physical space available for it at the next station or in a buffer), and the next job is immediately started if it is not starved (i.e., there is another job available from the upstream station or buffer). The key decisions in the design of asynchronous lines are buffer allocation—the capacity and placement of buffers—as well as the assignment of tasks to stations. It has been shown that asynchronous lines should not necessarily be perfectly balanced to maximize throughput; that is, a "bowl phenomenon" exists such that the middle stations of the line should be assigned less processing time than those at the beginning and end of the line (Hillier & Boling, 1966,1979). Smunt and Perkins (1985) found this phenomenon to be less pronounced for processes with lower levels of task time variance. Concerning the buffer-allocation problem, Conway, Maxwell, McClain, and Thomas (1988) found that small buffers are sufficient to offset much of the loss due to stochastic operation times, and that the placement of the buffers should be greater toward the center of the line for balanced lines or near bottlenecks if they exist (for a review, see Harris & Powell, 1999).

With regard to synchronous production lines, the timing of the job movement between stations is coordinated such that the all of the jobs are indexed simultaneously. In these lines, the tasks should be assigned to stations such that the station processing times are balanced. Synchronous lines can be further classified as paced or unpaced (Buzacott & Shanthikumar, 1993). A great deal of research has involved the development and testing of optimal and heuristic solution procedures for *paced* synchronous production lines in which there is a fixed cycle time at which the line is indexed. In the case of stochastic task times, there is a risk of not completing the tasks within the cycle time. These models are generally formulated with a cost-minimization objective (assuming the line is stopped until the units are completed or an off-line station is utilized to finish incomplete units) or by minimizing the required number of stations subject to a constraint on the probability of a station exceeding the cycle time. For a review of the literature on the basic line-balancing problem, see Scholl and Becker (2006); for generalized line-balancing problems, including a brief review of the stochastic line-balancing problem, see Becker and Scholl (2006); and for a taxonomy of line-balancing problems, see Battaïa and Dolgui (2013).

Rather than having a fixed cycle time, an *unpaced* synchronous production line advances only when all of the stations have completed their tasks. For example, the Conner Avenue assembly plant that produced the Dodge Viper utilized this type of production process:

> "Overall, the assembly process involves about 80 operations, performed during 37-minute stops at 30 stations along the line. The line is controlled by a light system—yellow indicates work is in progress at a station; green signals the assigned tasks at that station have been completed. Only when the entire line is "green" does the car move to the next station." (Dear, 2003).

Under this mode of production, there will be no incomplete units, as is possible with a paced line; all of the stations must now wait until the last station has finished its operations, rather than moving at fixed cycle times. On the other hand, the line can index as soon as all of the stations are finished, without waiting until the cycle time expires. Thus, rather than balancing the line such that there is a small probability of exceeding the cycle time (resulting in lower utilization and increased idle time), the line must be balanced based on the expected maximum time to complete the tasks of all of the stations. While this results in a variable throughput (not a fixed cycle time) with stochastic task times, this variability is expected to have minimal effect on the system due to the high volumes generally associated with assembly lines.

Although some analytic results have been presented for the operation of unpaced synchronous production lines (see, e.g., Buzacott & Shanthikumar, 1993), very little research has focused on balancing this type of line. Kouvelis and Karabati (1999) investigated mixed-model cyclic scheduling of unpaced synchronous lines but, again, they do not incorporate the line-balancing aspects. Chiang, Urban, and Xu (2012) developed a tabu-search metaheuristic as a solution methodology for a bi-objective line-balancing model that also considered throughput maximization. Doerr, Klastorin, and Magazine (2000) developed a cost-minimization line-balancing model with worker differences, daily production quotas, and planned overtime, and they assumed that task times followed a shifted-exponential distribution; our work differs from theirs as we model the

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