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Optimal flow-line conditions with worker variability

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ABSTRACT

When classical scheduling theory is applied to task sequencing problems, human characteristics are often not the primary consideration and their impact is often assumed away. In this paper, we examine the workforce scheduling problem in sequential flow line systems. We investigate the impact of within-worker and between-worker variability and discuss the selection of scheduling policies between fixed and work-sharing systems. The methodology includes human performance modeling with the objective to maximize throughput with general results with respect to productivity model. We are interested in determining and characterizing the optimal switching time between workers in work-sharing systems. A closed form solution is established in the case of two and three tasks with two workers. For a general number of workers and tasks we establish the maximum number of changes between assignments. We also establish a bound on throughput. Results allow one to solve workforce scheduling problems reduced complexity given the current set of bounds and conditions.

1. Introduction

Recent decades have witnessed profound changes in the role of workers in production systems. Workers were viewed as resources that could be replaced by automation (Baines and Kay, 2002). However, in several cases, the paradigm of a complete automation has failed. Because of this, we have seen a shift in interest towards systems in which workers' skills became more cognitive and their aptitudes provided the necessary level of flexibility. It has been discussed that in order to understand and improve productivity in manufacturing systems that rely heavily on human resources, a reliable description of both hardware and human components is fundamental (Becker et al., 2004; Buzacott, 2002). Technological aspects have received most of the attention, while the influence of human behavior on production systems has been underestimated. Tools that have been developed to support technicians during the design of production systems, consider workers as a simple resource, not characterizing their dynamic behavior. Production planning and designing systems are commonly built on the assumption that all workers are equal in their abilities and to perform at a steady pace. Worker differences and the variability in their performance have received little attention in operational models, in spite of a wealth of psychological research suggesting their relevancy even for simple manual tasks (Doerr and Arreola-Risa, 2000; Hunter et al., 1990; Rothe, 1978; Schmidt et al., 1988).

The flow-line is a production system in which jobs follow a fixed sequence of operations. Because of its usefulness and efficiency, flow-lines have been the subject of considerable research with the aim of finding optimal work-flow policies. In production systems, *work-flow* describes the motion of work between workers on the line, while *work-flow policy* is used to describe management methods that are available to control work flow. Two different types of work flow policies have been studied: fixed assignment systems (FAS) and work sharing systems (WSS). FAS also denotes fixed allocation of workers to tasks, the workload assigned to each worker does not change from batch to batch (a batch is a set of tasks to perform or a set of products to process) and the workload is completed within a physical zone or workstation. The stations where tasks are performed typically do not overlap. Within a WSS, the workload assignment is allowed to change from batch to batch. The change might to allow for preemption, or interruption. Some experimental studies have shown that a WSS is often preferred to a FAS. However there remains a lack of analytical understanding of when one policy will outperform the other.

This paper focuses on scheduling workers to tasks in a flow line by explicitly modeling individual performance differences including learning behavior. We study the impact of within-worker and between-worker variability when selecting the optimal policy between a FAS and a WSS. We will show that when maximizing throughput, the optimal policy depends on workers' learning and productivity characteristics. The methodology can be extended to also include other human performance characteristics such as

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forgetting. The remainder of the paper is organized as follows. Section 2 is devoted to the review of extant literature related to the worker-task assignment problem, while Section 3 studies the case of two and three tasks. In Section 4, we establish a bound on the maximum throughput from the flow-line. The importance of our results for the workplace is discussed in Section 5.

2. Literature review

The flow line has been the subject of considerable research, with an early focus on processes and less focus on worker performance or worker characteristics. Gagnon and Ghosh (1991) provide an extensive literature on assembly line research. A class of WSS models that acknowledges worker differences and relies on them for building dynamic assignments has been proposed. (Bartholdi and Eisenstein, 1996). Bartholdi et al. (1999, 2001) and Bartholdi and Eisentein (1996) are important expositions of the *bucket brigade* policy for work sharing, particularly with differential production speeds among workers. Under WSS, workers should be ordered from slowest to fastest for maximum efficiency (Bartholdi and Eisentein, 1996; Bartholdi et al., 2001) and the number of stations should exceed the number of workers. WSS depend on the difference between individual performances in ways that FAS do not. FAS models often assume that workers on a line are identical, and that variability is endemic to the tasks rather than to the workers (Doerr and Arreola-Risa, 2000). Within WSS models, workers on the line are often significantly different from each other. However, the within worker variability is assumed to be insignificant and thus, it is ignored. As mentioned by Doerr et al. (2004), the dominance of the WSS policy is accentuated by the *stability* of worker differences. In fact, the performance of a WSS may deteriorate and turn chaotic with upstream workers being blocked by downstream workers at unpredictable times and places. Although the work by Bartholdi et al. (2001) suggests that a WSS could perform well under certain kinds of variability, the literature on the impact of within worker variability on the performance of a WSS limited, and it is difficult to predict the conditions where WSS or FAS is the better policy. We assume that between workers' differences and within worker variability should be considered when determining optimal work-flow policy.

Models of variability in task completion times have been discussed on production line balancing (Kottas and Lau, 1981; Moodie and Young, 1965; Sarin and Erel, 1991), scheduling, and buffer locations, with the dominance of two approaches: a task approach, and a workload approach. The task approach assumes that a major source of variability in task completion times is the inherent variability of the tasks (Carraway, 1989; Wilhelm, 1987). On the other hand, the workload approach suggests that the environment (e.g., lighting, noise, and temperature) where the tasks are being performed constitutes the major source of variability (Baker et al., 1990; Powell, 1992). While these two approaches have been useful in some settings, the current study will consider the main source of variability to be the worker performing the task. Doerr and Arreola-Risa (2000) developed a worker-based approach for modeling variability in task completion. Results from the field experiment suggested that even in instances with fairly homogeneous workers and with tasks that vary a great deal, the major source of variability in task completion times was the worker performing the tasks, rather than the tasks themselves. This supports the hypothesis that the worker approach provides a better approximation than the task approach when modeling differential task completion times. The historical lack of attention devoted to worker variability in production systems is partly the consequence of an early focus on the setting of time standards and task's designed eliminate worker differences. The idea that differences among workers would be negligible once they are fully trained on *the best way to do things*, has oriented research on individual differences towards differential learning rates.

In this paper, we examine the flow line and model worker performance with a productivity function. The performance function quantifies the number of units being produced during a given period, and shows the worker's limiting characteristics (e.g., previous experience on the task or similar tasks, learning rate, forgetting rate, lapse of time since the last assignment to the task). We assume variability in the system is essentially due to both the worker performance variation with respect to the tasks, and the differences between workers. Hence, we solve the flow line scheduling problem acknowledging worker differences in the execution of the tasks. Research on scheduling has been focused on task to machine matching problems with interest on learning efficiency. Biskup (2008) provides a review on scheduling with learning. Huang et al. (2010) examined the case of single machine scheduling with time-dependent deterioration and exponential learning effects. Also, -Wu et al. (2012) investigated the single machine total weighted-tardiness scheduling problem with learning effects. A growing stream of research has started to address the case of the flow-shop environment. Koulamas and Kyparisis (2007) addressed the single-machine, and two machine flow-shop scheduling problem, including learning curves based on accumulated processing times. Cheng et al. (2012) examined the two-machine flow shop scheduling with a truncated learning function while minimizing the makespan, and Wu. et al. (2012) investigated flow shop scheduling problems with two machines and a truncated position-based learning function.

More closely related to the current study, a stream of work has considered the workforce's skills in the worker-task assignment problem. Warner et al. (1997) assigned workers to machine cells based on their human and technology skills. Bhaskar and Srinivasan (1997) proposed math-programming models for static and dynamic worker assignments that were problems in cellular manufacturing when minimizing makespan, and Norman et al. (2002) considered both technical and human skills in a team-based model for worker assignment in manufacturing cells, demonstrating that it needs to include human skills in worker training plans and assignment strategies in order to lead to better worker assignments. In a study of temporary workers in a mixed model flow line, Corominas et al. (2006) looked at scheduling considering both skilled and the unskilled workstations using a math integer program (MIP) approach. McDonald et al. (2009) extended this work by presenting a MIP model to assign cross-trained workers to tasks within a lean manufacturing cell when considering customer demand, skill requirement for tasks, quality, and job rotation, while minimizing current net cost. Corominas et al. (2010) addressed the task assignment problem when work performance depends on experience of all tasks involved. Lastly, Nembhard and Bentefouet (2012) established an optimal policy in parallel systems when maximizing throughput. The current study examines the more general flow-line system. That is, we will examine the flow line and define conditions for optimal choice between FAS and WSS policies. In the case of two tasks and a human performance model, the FAS may outperform the WSS policy when maximizing production. We will characterize the optimal switching time when work sharing has productivity advantages. The methodology will be extended to the case of three tasks. For the case with a general number of tasks, workers, and production time horizon we establish a lower bound on the maximum throughput.