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Dynamic Drum-Buffer-Rope approach for production planning and control in capacitated flow-shop manufacturing systems ☆

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ABSTRACT

Drum-Buffer-Rope-based production planning and control (PPC) approaches provide production managers with effective tools to manage production disruptions and improve operational performance. The corner stone of these approaches is the proper selection of time-buffers which are considered as exogenously defined constant. However, the majority of real-world manufacturing systems are characterized by the dynamic change of demand and by stochastic production times. This fact calls for a dynamic approach in supporting the decision making on time-buffer policies. To this end, we study a capacitated, single-product, three-operation, flow-shop manufacturing system. We propose a dynamic time-buffer control mechanism for short/medium-term PPC with adaptive response to demand changes and robustness to sudden disturbances in both internal and external shop environment. By integrating the control mechanism into the flow-shop system, we develop a system dynamics model to support the decision-making on time-buffer policies. Using the model, we study the effect of policies on shop performance by means of analysis of variance. Extensive numerical investigation reveals the insensitivity of time-buffer policies to key factors related to demand, demand due date and operational characteristics such as protective capacity and production times.

1. Introduction

Insufficient production planning in manufacturing systems often turns a non-bottleneck resource to capacity constraint resource (CCR), which operates as a bottleneck with on average excess capacity (Goldratt, 1988). Drum-Buffer-Rope (DBR)-based production planning and control (PPC) approaches focus on the synchronization of resources and material utilization in CCRs of manufacturing systems (Goldratt & Fox, 1986; Sivasubramanian, Selladurai, & Rajamramasamy, 2000). This synchronization calls for time-buffers that protect the production plans of CCR from the effects of disruptions at the preceding production resources. By means of time-buffers (i.e. constraint, assembly, shipping time-buffers), buffer management monitors the inventory in front of protected resources to effectively manage and improve system's performance (Schragenheim & Ronen, 1990; Schragenheim & Ronen, 1991).

The research agenda on the efficiency of DBR approach in PPC of manufacturing systems has received increased attention during the last decade. The basic assumption in all relative studies is the exogenous determination of time-buffers as a constant throughout the planning horizon. However, the majority of real-world manufacturing systems are characterized by the dynamic change of demand and by stochastic production times. Therefore, the decision making on time-buffer policies calls for a dynamic mechanism. This is exactly the purpose of this paper. More specifically, we consider a dynamic, capacitated, single-product, three-operation, flow-shop production system. We define as production time-buffer (PTB), the total of constraint and shipping time-buffers. We propose a dynamic, goal-seeking, feedback mechanism to define PTB for short/medium-term PPC. By integrating the proposed mechanism into the flow-shop system, we develop a system dynamics (SD) model to support the decision making on PTB policies. We study the shop response (dynamics of product flows, inventories, performance measures) to PTB policies under stochastic demand and production times. Since the dynamic behavior may be used to evaluate the efficiency of a specific PTB policy, the SD model can be viewed as a decision support system (DSS) for PTB-related decisions. In particular, by continuous monitoring, the actual level of PTB is adjusted to demand-driven desired values. The innovative element of the control mechanism is the endogenous definition of desired PTB values. In addition, the mechanism provides robustness to sudden disturbance occurrences in demand and shop operations. This is a positive property to cope with uncertainty issues in both external and internal shop environment. Using the SD model, we determine PTB increase/decrease policies throughout a given planning horizon and we study their effect on shop performance by means of analysis of

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variance (ANOVA). The examination of results obtained by extensive numerical investigation reveals the insensitivity of PTB policies to key factors related to demand, demand due date and operational characteristics such as protective capacity and production times. This is an additional appealing feature of the proposed PTB control mechanism which provides production managers with flexibility on PTB-related decisions.

The rest of the paper is organized as follows. Section 2 presents the literature review on DBR studies and applications in manufacturing systems and justifies the suitability of SD methodology in developing dynamic DBR-based PPC systems. Section 3 contains the flow-shop system under study and its performance measures, the description of the SD model, the mathematical formulation and the model's validation. Section 4 presents the control parameters under study along with their sets of values, while Section 5 presents the adaptability and robustness properties of the dynamic PTB control mechanism. The effect of PTB policies on the shop's performance obtained by numerical investigation is given in Section 6. Finally, in Section 7 we wrap-up with a summary, the limitations of our work and directions for model extensions.

2. Literature review

Review papers present a variety of PPC problems dealing with flow-shop scheduling in manufacturing systems; either with sequence-independent set-up times or sequence-dependent set-up times (Hejazi and Saghafian, 2005; Zhu & Wilhelm, 2006). The proposed scheduling methods include: (i) exact methods such as dynamic programming (Held & Karp, 1962), branch-and-bound (Grabowski, Skubalska, & Smutnicki, 1983), integer programming (Frieze & Yadegar, 1989) and complete enumeration; (ii) heuristic methods such as Palmer algorithm (Palmer, 1965), Gupta algorithm (Gupta, 1971), CDS algorithm (Campbell, Dudek, & Smith, 1970) and NEH algorithm (Nawaz, Enscore, & Ham, 1983); and (iii) metaheuristic methods such as simulated annealing-SA (Liu, 1999), genetic algorithms-GA (Reeves, 1995), tabu search-TA (Widmer & Hertz, 1989), greedy approaches (Carpov, Carlier, Nace, & Sirdey, 2012), variable-depth search approach (Jin, Yang, & Ito, 2006), pilot methods (Voβ, Fink, & Duin, 2005), hill climbing procedures (Nearchou, 2004), ant colony system-ACS (Rajendran & Ziegler, 2004), artificial neural network-ANN (Lee & Shaw, 2000) and hybrid algorithms (Wang & Zheng, 2003).

For the specific make-to-order flow-shop environment, Stevenson, Hendry, and Kingsman (2005) provide a detailed review on the employed PPC approaches. The commonly used approaches include Constant Work In Process-CONWIP (Framinan, González, & Ruiz-Usano, 2003), Workload Control-WLC (Thűrer, Stevenson, & Silva, 2011), Material Requirement Planning-MRP (Bertrand & Muntslag, 1993), Just-in-Time-JIT (Singh & Brar, 1992), Theory of Constraints-TOC (Atwater, Stephens, & Chakravorty, 2004; Goldratt & Cox, 1984; Mabin & Balderstone, 2003), Paired cell Overlapping Loops of Cards with Authorization-POLCA (Riezebos, 2010) and web- or e-based Supply Chain Management-SCM (Cagliano, Caniato, & Spina, 2003; Kehoe & Boughton, 2001). The comparison of MRP, TOC and JIT approaches justifies the TOC to be more effective for a pure flow shop or general flow shop system, when the bottleneck resources are stationary positioned in the production process. The effectiveness of TOC approaches is further discussed for highly customized industries facing difficulties in estimating in advance the processing times (Stevenson et al., 2005). This is due to the fact that TOC requires data accuracy only in CCR to control the plant throughput (Gupta & Snyder, 2009).

TOC was first developed in the mid-1980s (Goldratt & Cox, 1984; Gupta, 2003). It uses the DBR production scheduling approach; production process is scheduled to run in accordance with the needs of the CCR, as CCR determines the performance of the whole production system. The advantages of TOC are discussed in various industrial implementations reporting the reduction of inventories by 49% and the improvement of due date and financial performance by 60% (Gupta, 2003; Mabin & Balderstone, 2003). The statistical analysis of a survey with questionnaires to manufacturing managers performing TOC, JIT and traditional methods provides further insights regarding the superiority of TOC approaches on other approaches in terms of financial and operational performance measures (Sale & Inman, 2003). TOC has also been used for the determination of optimal, or near optimal, product mix decisions (Aryanezhad & Komijan, 2004; Souren, Ahn, & Schmitz, 2005).

In certain studies, the usefulness of DBR logic in PPC of manufacturing systems is revealed by conducted simulation experiments under different manufacturing settings. In these studies time buffers are not optimized and remain constant throughout the simulation process. In a make-to-stock environment, DBR-based PPC is combined to manufacturing expediting of products (Schragenheim, Cox, & Ronen, 1994). In a make-to order environment, DBR approach is combined with different order review/release policies (Russell & Fry, 1997) and it is compared to the previously used approach in furniture manufacturing firms (Wu, Morris, & Gordon, 1994). In a serial production line with exponentially distributed processing times setting, DBR-based PPC is compared to CONWIP approach (Gilland, 2002). The difference between the two approaches is that in CONWIP approach material units are released into the line at a rate equal to line throughput, while in DBR approach at the rate they are produced at CCR. The outperformance of DBR approach is proved to increase as CCR moves closer to the first operation of production as well as when the required throughput or service level is close to the system's capacity (Framinan et al., 2003). Finally, in a flow-shop setting, Sirikri and Yenradee (2006) employ DBR-based PPC and investigate how buffer sizes related to lead time up to CCR affect specific performance measures.

The analytical approaches to determine time-buffer sizes based on queuing theory are limited in simple PPC manufacturing problems. In these approaches the constraint resource is modeled as a M/M/1/K system (Radovilsky, 1998), while the production system is modeled either as a determination model, where a tree structure represents the relationship between the constraint machine and its feeder machines (Tu & Li, 1998; Ye & Han, 2008) or as multiproduct open queuing network in which the production operations are modeled as GI/G/m (Louw & Page, 2004).

The applicability of DBR in real world case studies is denoted by a lot of DBR implementations in manufacturing firms; e.g. in Orko-Pak in Netherlands that manufactures packaging material from corrugated cardboard (Riezebos, Korte, & Land, 2003), in Oregon Freeze Dry processing products by removing water at low temperature and pressure (Umble, Umble, & von Deylen, 2001), in Alameda Naval Aviation Depot that remanufactures aircraft, jet turbine engines, engine components and avionics equipment (Guide & Ghishelli, 1995), in a light assembly firm for heavy duty trucks and trailers (Pegels & Watrous, 2005) and in a bearing manufacturing company (Steele, Philipoom, Malhotra, & Fry, 2005). DBR is even used in a fighter squadron of the Israeli Air Force for better scheduling of its missions and allocating crews to aircraft (Ronen, Gur, & Pass, 1994).

DBR literature suggests several performance measures in evaluating the efficiency of the proposed approaches. These measures include: the average system throughput, the average finished product inventory, the average number of stockouts (Duclos & Spencer, 1995); the throughput, the utilization of machines, the average wait time of items, the percentage of machine blocking (Mahapatra & Sahu, 2006); the mean percent