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An analytical approach to improving due-date and lead-time dynamics in production systems

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ABSTRACT

A deterioration of due-date reliability is often attributed by planners to external causes rather than to their own planning behavior. Particularly, planners tend to underestimate the effects of time delays, and may not sufficiently take control actions into account that have been initiated but are not yet demonstrating any effects. Unfavorable dynamic behavior can result if planners react inappropriately to short-term decreases in due-date reliability and, for example, use their intuition to adjust planned lead times. A better understanding is needed of the impact of time delays and lead-time-related adjustments on resulting system behavior and of how often plans and associated work releases should be adjusted in practice.

In this paper, two planning and control approaches are modeled and analyzed: First, a production system is modeled in which planned lead times and work input are adjusted periodically if the average lead time deviates from the planned lead time. Second, a production system is modeled in which regulation of lead time towards a planned lead time is accomplished by adjusting the work input. For both approaches, discrete (z-transform) equations are obtained that allow trends in dynamic behavior to be characterized as a function of delays in obtaining production information, and delays in making lead time adjustment decisions and implementing them. Industrial data from a steel-producing company are used to illustrate the potential effects of time delays and of averaging of lead time data, as well as to illustrate how analytical results can be used to guide selection of the adjustment period and of lead time regulation parameters. The analytical approach presented here can be used as a tool for quantifying and guiding improvements in the performance, the robustness, and the agility of production systems. This is of particular interest with respect to cyber-physical technologies such as autonomous data collection and embedded models that present significant future opportunities for reducing delays in decision making and decision implementation.

1. Introduction

Lead time oscillation and instability can pose a problem for modern manufacturing resource planning (MRP II) and Enterprise Resource Planning (ERP) systems if planners react inappropriately to short-term decreases in due-date reliability and use their intuition to adjust planned lead times rather than applying scientific understanding [1,2]. Lead time is defined here as the time from the release of an order to the production system until the order leaves the system. This includes the sum of the interoperation time (waiting time, transport time, setup time) and the operation time [3,4]. Lead time instability can be a result of poor support from Production Planning and Control (PPC) systems with regard to determining and implementing appropriately planned lead time adjustments [3]. Disturbances in production processes often contribute to low logistic achievement of targets, such as short lead times, low work in process (WIP), high capacity utilization, and high due-date reliability [4]. Increasingly networked manufacturing systems and the complexity of interdependencies of their logistic targets [5–7] make production planners uncertain about their actions and prone to take precautions [2,8,9,10]. In production systems with customer due-dates, backward planning approaches are typically used. For these systems, a common strategy for increasing due-date reliability is to extend the planned lead times in the MRP master data [11]. This leads to earlier order releases, increased WIP levels, lengthened lead times, and increased process workloads, all of which tend to make lead times more erratic [12]. Increasing numbers of urgent orders become high-priority rush orders, and this

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results in increasing sequence perturbations and increasing lead time standard deviation. Although the goal was to increase due-date reliability, this cycle leads to lower due-date reliability, with planners then taking further measures. Ultimately, mean lead times can reach a high level as described by the term "lead time syndrome of production control", which has been observed in systems using backwards scheduling [13,14]. This is a common approach in practice, for instance in ERP software [15].

When making decisions regarding complex production systems, planners tend to anchor on information readily at hand and then make adjustments until a plausible estimate or acceptable value has been reached [16,17]. It has been shown that, in practice, planners tend to underestimate the effects of time delays [18]. A deterioration of due-date reliability is attributed often to external causes rather than to their own planning behavior. Particularly, planners may not sufficiently take control actions into account that they have initiated but that are not yet demonstrating any effects. Several researchers have proposed measures for preventing or mitigating planning instability. Examples include assembly control [19], logistic positioning [20], and use of MRP II to avoid any "phony backlog" [21]. Studies of organizational and human influences on planning stability have referred to the "planning bullwhip" as a term encompassing instabilities in planning [1,22,23]. The influence of planned lead time updates on the performance of planning systems has been studied by means of clearing function theory [19,21], and increasing the period between planned lead time adjustments (i.e. decreasing the latter's frequency) has been suggested in order to decrease process variability [23]. However, the significant time delays that exist in practice between calculating and implementing planned lead time adjustments, as well as time delays in measuring changed system states, have not been considered, and a method for determining an appropriate adjustment period has not been presented. Moreover, recent studies have shown that long periods between adjustments can result in significantly lower system performance, and that delays significantly influence planning instability [24]. Time-scaled simulations were used [12] to assess due-date reliability in the presence of the lead time syndrome of production control, and it was concluded that the period between adjustments in planned lead time should not be shorter than the sum of delays.

Previous work by these authors [25] showed that control-theoretic analyses can be used to predict lead time instability in production systems and theoretically confirmed previous observations regarding the relationship between time delays and the period between adjustments in planned lead time. Control-theoretic analyses in the continuous and discrete time domains have been applied to production planning and control [26], as well as to ordering and inventory control [27] and supply chain management [28,29] in both continuous and discrete time. In this paper, the primary focus is on the time required to recover from disturbances, a characteristic also referred to frequently as the "resilience" of a system [30]. The time to recover as well as the impact of lead time adjustments on system behavior is similar to the concept of resilience [30,31]. Resilience can be defined as "the capability and ability of an element to return to a stable state after disruption" [30]. In the context of production systems, several definitions of and modeling approaches for resilience exist. For instance, [6] defines the resilience of a production system as the ability "to survive a disruptive event" and [32] defines resilience as the "capability to recover their functions after partial damage" [33]. Due to the rather general character and the focus on more negative events (see the previous definitions: "disruption", "disruptive", and "partial damage") in the resilience definitions, we will use the term "time to recover" as a specific measure and to avoid indicating that the adjustment of a planned lead time is necessarily a negative event.

A better understanding is needed of the impact of time delays and lead-time-related adjustments on resulting production system behavior. Therefore, the goal of this investigation is to better understand how often to adjust plans and associated work releases in practice in order to improve due-date reliability by avoiding unfavorable lead time dynamics in production systems. First, an analysis is presented for production systems in which adjustments are periodically made to planned lead time when the measured average lead time deviates from the plan. Discrete time equations are obtained that dynamically relate key system variables to variations in work input and output. These equations are combined and transformed to allow trends in dynamic behavior to be characterized as a function of delays in obtaining information from production, making planned lead time adjustment decisions and implementing them. Regions of parameter values are identified for which the time to recover from disturbances is expected to be favorable. Next, an analysis of regulation of lead time is presented, which is an alternative approach where the goal is to maintain mean lead time close to a planned lead time target. Industrial data from a steel-producing company are then used to illustrate the potential effects of time delays and averaging of lead time data in practice, as well as to illustrate how the analytical results can be used to guide selection of the adjustment period. Finally, conclusions are drawn and recommendations are made regarding further research.

2. Analysis of planned lead time adjustment

In those production companies that have many product variants and small production series, production mainly takes place in flexible job shop environments. Based on a specific customer order, the production processes necessary for an individual product are planned backwards, starting from the externally set customer due-date. Based on planned lead times for each production process stored in the ERP system, the time required for each production step and for the interoperation times (waiting and transport times) is defined in order to identify the right time for releasing the order to production. After production completion, the customer due-date and the actual completion date are compared to calculate the due-date reliability. In recent years, due-date reliability has become one of the leading key performance indicators (KPIs) in industrial practice. If customer due-dates are missed repeatedly, it is common practice to adapt the planned lead times in order to improve the planning basis (and therefore due-date reliability). However, planned lead time adjustments are usually not accomplished as part of a defined process, but rather spontaneously as a quick reaction to low due-date reliability and without profound knowledge of the extent to which master data of the ERP system should be adapted. This approach can have severe negative consequences for the performance of a production system, a phenomenon already being described in the 1970s as the "vicious cycle of production planning" [13].

The planned lead time adjustment cycle that has been modeled is illustrated in Fig. 1: actual lead times are measured; mean lead times are calculated; planners adjust planned lead times with the goal of eliminating differences between planned and actual lead times; work in progress is adjusted to implement lead time adjustments; production system loads change; the mean (and variance) of lead times changes and due-dates are again missed; planned lead times are adjusted again, etc. This (re)planning cycle is assumed to be repeated every T shop calendar days (scd). The difference between actual lead time and planned lead time can be referred to as the relative lateness [33,34]. A positive lateness indicates that the actual lead times are longer than originally planned. The problem that actual values of lead time often differ from planned values, requiring manufacturing parameters to be continually adjusted, resembles a classical control problem [35,36] where significant time delay components tend to induce oscillatory system behav-