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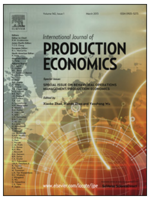

Empirical validation of meta-models of work centres in order release planning

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ABSTRACT

We consider the problem of planning future order releases in hierarchical production planning and control systems. An established research direction is the clearing function concept: The planned material flow through a production unit is modeled by inventory balance equations for WIP and final products, and the consequences of the stochastic properties of the material flow are modeled by *clearing functions*, which represent the functional relationship between the level of WIP and the maximum output of a work centre in a period.

Theoretical insights suggest that modeling the output of a work centre in a period as a function of *one* independent variable is not sufficient for this type of models because of the time-varying transient states. This paper tests one- and two-dimensional clearing functions on simulation and empirical data obtained from a make-to-order production system. The fit of the clearing functions will be made by a regression through the origin and evaluated by the adjusted R^2. The fits of the different clearing functions differ depending on the source of data. The possibilities for improvements by adding independent variables depend both on the period length and on the stationarity of the process. The findings lead to suggestions which additional independent variables should be added to a clearing function in order to improve the estimation of a work centre's future output and hence improve order release planning models.

1. Problem description

Manufacturing planning and control (MPC) systems play an important role in managing the flow of material through manufacturing organizations. Over the last 50 years many production planning systems were designed. It started with the Bill of Material (BOM) explosion in the 1960s which evolved into hierarchically organized systems like Material Requirement Planning MRP (Orlicky, 1975) and MRPII (Wight, 1983) twenty years later. These in turn led to today's modern structures like Enterprise Resource Planning Systems (ERP) and Advanced Planning Systems (APS) (Bertrand et al., 1990; de Kok and Fransoo, 2003; Stadtler and Kilger, 2005). All of these approaches try to optimize the material flow through the company, between manufacturing plants, vendors and other stakeholders as well.

MPC systems, especially for discrete manufacturing, are often structured hierarchically and consist of two levels. The top level coordinates the production units that constitute the logistic chain by coordinated releases of production orders and thus sets the targets for the production units. The base level performs detailed scheduling within the production units. The interface between the top level (Supply Chain Operations Planning) and the base level (production unit control; for these terms, see Bertrand et al., 1990; De Kok and Fransoo, 2003) is *order release* which is defined as the transfer of the control over the respective work orders from the top to the base level, that is, to the decision making units within the production units. Releasing orders at the right time in order to maintain short, predictable flow times and high due date performance requires an anticipation function (Schneeweiss, 2003) that predicts the flow times of the work orders as a function of the order release decisions. The paper deals with this anticipation or modeling task. More specifically, we concentrate on multi-period models for order release planning that optimize order releases based on an anticipation of the material flow that results from specified release quantities over time.

These models represent the production unit as a network of work centres $j=1,\ldots,J$. The planning horizon is divided into planning periods $t=1,\ldots,T$. The material flow is represented by inventory balance equations for WIP at each work centre and for final products, usually distinguishing different products or groups of products with similar routing. Since the material flow is modeled as continuous, the resulting network flow model is a fluid model in discrete time.

A crucial topic for this type of models is the highly nonlinear relationship between work-in-process (WIP), average flow time

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and output which is well-known from simulation (e.g., Wiendahl, 1995) and queueing models (e.g., Hopp and Spearman, 2008).

There are essentially two ways to consider this relationship in order release models. Models with fixed lead times that are based on the workload control concept are extensions of Input/Output Control introduced in the 1970s (see Wight, 1970; Plossl and Wight, 1973; Belt, 1976). These models aim at keeping the level of WIP, measured in hours of work, at the work centres at a level that is consistent with the flow time norm (see, e.g., Kingsman, 2000; de Kok and Fransoo, 2003). The models are relatively straightforward and seem to perform well compared to traditional order release mechanisms that are based on the workload control concept (Puergstaller and Missbauer, 2012). Performance is measured by indicators like stock keeping unit (SKU) inventory, WIP level and due-date performance that result from the actual or simulated material flow that is controlled by the order releases determined by the model. However, a fixed lead time constraint in order release models imposes essential limitations especially in the case of time-varying demand. Using fixed lead times requires a norm-setting decision level that determines the target lead times (see de Kok and Fransoo, 2003, p. 617ff.). The impact of time-varying demand on the performance of fixed lead time models must be seen in this context. Therefore, the topic of this paper are models that allow time-varying and hence load-dependent lead times. In this case the nonlinear relationship between WIP, flow time and output must be represented in the model.

Models of this type determine order releases, output and time-varying lead times simultaneously over time. There are several ways to design models that perform this task (for overviews, see Missbauer and Uzsoy, 2011; Puergstaller and Missbauer, 2012). We limit our attention to clearing function models. A *clearing function* is defined as the functional relationship between an appropriate measure of WIP at a work centre j in period t and the expected or maximum output of this work centre j in period t. Clearing functions model the effects of the discontinuity and stochasticity of the material flow at the work centres that limit the possible output. They can be interpreted as meta-models and avoid analytical descriptions of the queueing processes in the manufacturing system. In line with queueing-theoretical results, usually a concave, saturating shape of the clearing function is assumed as suggested by Karmarkar (1989). The clearing functions of the work centres are nonlinear constraints to the output and are usually approximated by a set of linear functions (tangents). The resulting linear program assigns capacity to products in a manner that satisfies a set of constraints that represent system capacity and dynamics at an aggregate level and eventually yields the optimal release quantity per product and period.

Clearing function models have been described and tested extensively by simulation (see Missbauer, 2002; Asmundsson et al., 2006, 2009). Asmundsson et al. (2006, 2009) show that clearing functions, when estimated correctly, produce production plans that are much more aligned with the ability of the production system to execute them compared to fixed lead time approaches. They compare the performance of clearing function formulations to that of a conventional fixed lead time model in a semiconductor wafer fabrication facility and find that the clearing function models yield significantly better on time delivery than the fixed lead time model. However, clearing function models tend to exhibit problematic behavior, namely short-term oscillations of the planned release quantities, as a response to sudden changes of the demand. Moreover, it is difficult to model the product mix of the output in a certain period that results from the product mix of the work input or of the WIP, respectively. This indicates that modeling the material flow by clearing functions imposes certain limitations.

We limit our attention to one aspect of this modeling task, namely the dependence of the total output (aggregated over the products) in a certain period t on the history of the process (work input and output over time) that leads to a certain WIP level in period t.

Conventional clearing functions assume that the output in period t can be modeled as a function of *one* independent variable (WIP level or available work, termed *load*, in the period under consideration) to a sufficient degree of accuracy. This holds for steady-state situations, and likewise a clearing function can be formulated for specified transient states like, for instance, the first period in the ramp-up phase of a queueing model (Missbauer, 1998, p. 250ff.). However, in the actual operation of a production unit steady-state situations and various transient states can occur in any sequence, and this trajectory of the system is controlled by the order release decisions that are made by the model. Hence “the clearing functions employed by most researchers to date represent an average relation over a wide range of operating states, but may be quite inaccurate for a given sample path of system evolution.” (Kacar and Uzsoy, 2010). Therefore, we must ask whether a one-dimensional clearing function is sufficient.

The numerical analysis of one transient period of an $M/M/1$ model in Missbauer (2011) indicates that this is not the case. The expected output in the period given a certain expected load (available work) in the period can strongly depend on the composition of the load and on the uncertainty of the initial WIP. Meaning that on the one hand it depends on the proportion of initial WIP and work input (that together constitute the load) and on the other hand on the probability distribution of the initial WIP. These insights suggest that the history of the process and the uncertainty of the load estimation influence the output in a period t that can be expected given a certain estimated load. *This leads to the hypothesis that a multi-dimensional clearing function where the independent variables reflect the process history and the uncertainty of the load estimation lead to improvements of the fit of these functions to different data sets compared to the usual one-dimensional clearing function*.

The contribution of this paper is twofold: Firstly, we test whether an extension of the state-of-the-art clearing functions by adding independent variables leads to improvements of the fit of these functions to different data sets. We use empirical data obtained from a make-to-order production system and simulation data obtained from a scaled-down model of the same production system. In order to explore specified structural properties we also analyze data obtained from two single-stage queueing systems. We fit existing and extended clearing functions to these real industry data as well as to the simulation data. This will be tested by running regressions through the origin with up to three independent variables. All regressions will be performed with linear and nonlinear functions. The improvement of the fit is measured by comparing the adjusted coefficient of determination of the various models.

Secondly, we expand this discussion by analyzing the fit of the clearing functions for simulation and empirical data; the latter, to our knowledge, has only been published once in this research area by Fine and Graves (1989). This paper tries to fill this gap and aims at stimulating the discussion of the applicability of clearing function models in practical settings. We hope to get insights from empirical data that are either not apparent from simulations, like the influence of human related factors, or are different to simulation data like the amount of spread in the data. Hence, we expect different findings concerning our hypotheses depending on the source of the data.

The remainder of this paper is structured as follows: Section 2 describes the relevant literature regarding clearing functions and derives the hypotheses that are tested. Section 3 outlines the used method to estimate the clearing functions from the obtained empirical and simulation data. In Section 4 we describe the real