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Autonomous Control in Serial Production with Time-Continuous and Discrete Event Models

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Abstract: This paper presents a new approach for controlling serial production lines. Thereby, discrete event and time-continuous simulation are used and the utility of both methods is compared, concerning precision of the outcomes, as well as user friendliness. The main contribution is an autonomous control approach in an exemplary flow shop scenario with two production lines including three processors in each case. Two different types of products are produced in the presented production environment, whereas each type is preferably produced on one of the lines. The presented strategy enables the products to decide themselves which production line has to be chosen depending on the evolution of the inventory within the production environment.

1 Introduction

In classical production planning and control systems a central planning and controlling supervisory pre-plans all flows of parts and processes within the production network. This includes standard processes as well as deviation management in case of machine failures or absence of material. However central planning and control can yield suboptimal performance of the system which results in lower efficiency. In complex system it can even cause unforeseen dynamic effects (cf. SCHOLZ-REITER et al. 2008, p. 128). For this reason the benefits of autonomous control strategies are discussed for production planning and control as well as in logistics in recent literature (cf. SCHOLZ-REITER et al. 2008). Fundamental theories, adopted from nature's principles which can be especially used for controlling complicated processes, are already described in past publications (cf. BRUECKNER 2000). Different aims can be achieved by introducing autonomous control to production systems. These are the classical aims of production logistics like minimizing inventory, maximizing throughput or minimizing throughput times (cf. GÜNTHER, TEMPELMEIER 2009, p. 9). Since inventory costs are high and often the space for buffers is limited, we are looking for an autonomous control strategy which is able to lower inventory in a production system. Since serial flow shop production is typical for the automotive industry which counts a respectable part of industry nowadays, we are looking for approaches which can handle the complexity of a serial flow shop production especially by handling a lot of different variants and a large workload. There are different methods to analyze autonomous control strategies in given flow shop scenarios. The paper ties in with an analytic model approach (cf. DACHKOVSKI et al. 2006) controlling a shop floor consisting of two parallel machines producing two product types. Our approach is extended to two parallel production lines to analyze the behavior of a serial production environment. For the beginning, only two different product types are considered, however it builds a fundamental basis for enlarging the system to assess the behavior regarding a high number of different variants. Dynamic modeling of production and logistic systems is mostly done by simulation models. In this paper a discrete event and a time-continuous simulation model of the developed control strategy are performed and compared. Nearly a quarter century discrete event simulation (DES) has been dominating simulation methods in production and logistics (cf. WENZEL et al. 2010, p. 73). Hence, together with new control methods, new modeling approaches are gaining more attention within the production and logistics world, e. g. time-continuous models which can perform fluid approximation models of serial production lines. Here the rate of change of a queue in front of a machine is given by the inflow into the queue respectively the machine, minus their outflow (cf. ARMBRUSTER et al. 2005, p. 5). But most of these fluid models are coupled with partial differential equations, which will only make sense if the spatial state of a production lot is important for its control. We assume that in the considered production and logistics systems the inventory only changes over time, but not over space. Therefore, we have to look at the flow of the parts rather than at the density. In the paper, we will compare the outcomes of a discrete event simulation model with those of a time-continuous simulation model, in order to see how each simulation method performs within the considered environment.

Section 2 gives a short overview of dynamic analysis methods for production and logistics systems. In section 3 the new control strategy is worked out, whereas 3.1 characterizes the assumed production scenario, section 3.2 describes the time-continuous model, section 3.3 the discrete event model, in section 3.4 the control model is revealed and 3.5 points out the simulation results which are gained by using the numeric computing environment MATLAB for the time-continuous model. The discrete event model is implemented by using MATLAB SimEvents. We chose MATLAB as a tool which is capable of both time-continuous and discrete event simulation. In section 4 the comparison of discrete event and time-continuous simulation is shown and section 5 wraps up the results in a summary and is completed by a conclusion of the presented research.

2 Dynamic modeling approaches in production and logistics

In this section, we shortly describe the methods, we recognized in recent literature, for analyzing dynamic behavior in production and logistics.

Coming from physics, *cellular automata* represent discrete models for dynamical systems in order to investigate turbulence, chaotic behaviour and dynamics outside stability points (cf. BRUECKNER 2000, p. 7). *Petri nets* are a general formulation of automats and part of the class of analytical models. They are capable to show characteristics like deadlocks or reversibility of production and logistics systems (cf. KIENCKE 2006, p. 307). With the help of the *Max-plus algebra* discrete event systems can be described and analyzed analytically by using the large mathematical toolkit of the linear algebra. Furthermore the simulation is fast and efficient, similar to differential equations (cf. SCHOLZ-REITER et al. 2008, pp. 116). By using *queueing models*, probable relationships between the waiting time and the length of the queues as well as the service station's utilization times can be predicted, but probability distributions are assumed which cannot be guaranteed in practice (cf. NYHUIS, WIENDAHL 2008, p. 41, p. 48). In *discrete event simulation*, state transitions of the considered system are observed over time. The system is mapped by events, processes and activities (cf. KUHN, WENZEL 2008, p. 79). Maximizing the flexibility of production systems is one of the main targets of *agent systems*. It is especially suitable for shared organizational structures. Thereby the decision making is done by cooperation of several decision makers. The local coordination of processes in distributed production networks gives a perfect field of application for cooperating agents. Multi-agent systems shall simplify the cooperation between different companies (cf. PAWELLEK 2007, pp. 109). By approximating the behavior of a queueing process with differential equations, a *time-continuous simulation model* is obtained. Here either ordinary differential equations, describing the system's behavior over time, or partial differential equations, mapping the system's behavior over time and space (cf. ARMBRUSTER et al. 2005) can be used for modeling.

3 Autonomous control scenario in production flow shop

In the following section an exemplary scenario in a production logistic environment is rolled out in order to derive the control approach and execute it in discrete event and time-continuous simulation. The scenario is motivated by DASHKOVSKI et al (2004) as well as SCHOLZ-REITER et al. (2005), however contrary to them, a serial production instead of a shop floor is considered. The parameter values correspond mainly to those examined by GÖTTLICH et al. (2006).

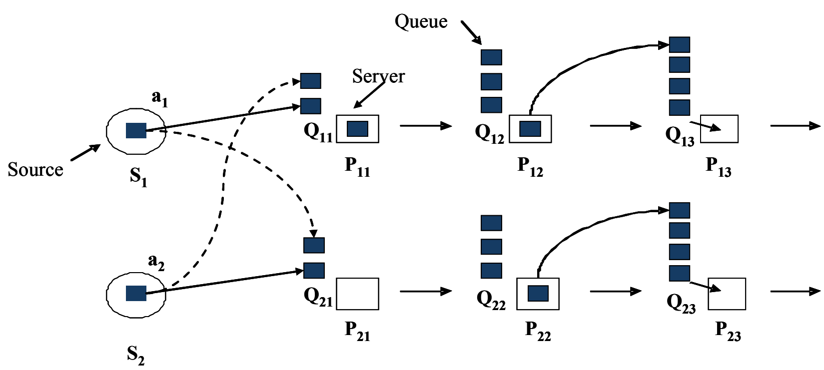

Figure 1: *Flow shop scenario*

3.1 Flow shop scenario

The autonomous control is performed within a flow shop scenario consisting of two separate production lines which is shown in Figure 1. The parts arrive with arrival rate a_1 from source S_1 and arrival rate a_2 from source S_2. Without control, all parts from S_1 proceed to production line 1 and all parts from S_2 proceed to production line 2. Since we are modeling a serial production, once a production line is chosen, it cannot be changed again. In DACHKOVSKI et al. (2006) and SCHOLZ-REITER et al. (2005) the authors assume that parts have always the chance to interchange between the production lines. Production line 1 consists of three processors P_{11}, P_{12}, P_{13} with three queues Q_{11}, Q_{12} and Q_{13} and production line 2 consists of three processors P_{21}, P_{22} and P_{23} with three queues Q_{21}, Q_{22} and Q_{23}. The processors within production line 1 have the capacities c_{11}, c_{12}, c_{13} and the processors within production line 2 have the capacities c_{21}, c_{22}, c_{23}.

3.2 Continuous model

The evolution of the buffer queues within the production lines can be considered as a system of coupled ordinary differential equations. The general formulation of the differential equations of the queues is given by

$$\dot{Q}_{ij} = P_{ij}^{in} - P_{ij}^{out} \tag{1}$$

with: P_{ij}^{in} inflow into processor and P_{ij}^{out} outflow of processor

Since we model a serial production line where the output of one processor is fed into the next processor and can further assume that no goods are gained or lost during the production processes the system satisfies:

$$P_{ij}^{in} = P_{(i-1)j}^{out} \tag{2}$$

We process fractions in a time-continuous system rather than single parts, so the inflows into production line 1 and 2 can be described with the equations

$$P_{11}^{in} = \alpha_1 + \beta_1, P_{21}^{in} = \alpha_2 + \beta_2, a_1 = \alpha_1 + \alpha_2, a_2 = \beta_1 + \beta_2 \tag{3}$$

3.3 Discrete event model

In order to perform a discrete event simulation model to incorporate autonomous control within the described flow shop scenario, standard treatment of the system is enhanced. Within the simulation, the events are considered as deterministic, stochastic behavior is during the first modeling step not part of the analysis and will be analyzed in further research. In a discrete event simulation, different methods of internal process control can be used, like time control, event scheduling, activity scanning, process- interaction, transaction flow (cf. KUHN; WENZEL 2008, pp. 79). In the given context we use the event-based approach. In Figure 2 an exemplary extract of the implemented system is shown as a SimEvents screen shot.

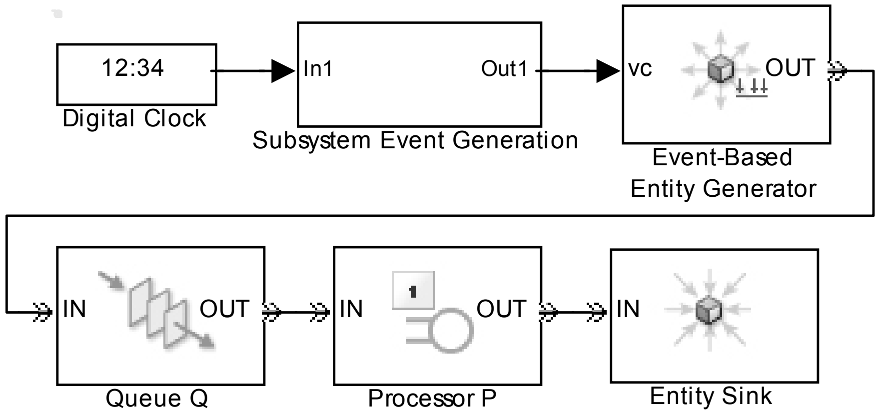

Figure 2: *Exemplary extract of the discrete event model in SimEvents*

3.4 The control model for time-continuous and discrete event simulation

In our model, we perform a control method, minimizing the inventory of the given production scenario. Since the production inventory is given by the content of the queues in front of each processor, the objective function of the optimization problem is given by minimizing the sum of the queue contents. To define the inventory minimizing control parameters, each possible state of the system is assessed by looking at the current buffer states and choosing the production line with the lowest sum of buffer contents by using

$$Q_1^*(t) = Q_{11}(t) + Q_{12}(t) + Q_{13}(t), Q_2^*(t) = Q_{21}(t) + Q_{22}(t) + Q_{23}(t) \quad (4)$$

Here, Q_1^* and Q_2^* denote the sum of the buffers in production line 1 and production line 2 at time t, respectively. The autonomous control is performed in a new approach which is only suitable for systems of the serial production, where the outflow location of the production line is determined by the inflow position. Table 1 shows the derived control parameters for the controlling approach in the time-continuous model.

In the discrete event model we choose the line with the smaller queue.

3.5 Simulation results

For the simulation we assume following processing capacities for both production lines: $c_{11} = c_{21} = 1/15, c_{12} = 1/10, c_{22} = 1/8, c_{13} = c_{23} = 1/15$. Figure 3 shows the continuous inflow profile of the parts, used in the time-continuous model and an extract of the variable generation times of the parts for the first production line, used in the discrete event system. The inflow of the second production line is the same as the inflow of the first, but delayed for 20 time units.

	$Q_2^* = 0$	$Q_2^* > 0$
$Q_1^* = 0$	$\alpha_1 = a_1$, $\beta_2 = a_2$, $\alpha_2 = 0$, $\beta_1 = 0$	$\alpha_1 = a_1$, $\beta_2 = \begin{cases} \min(a_2, c_2^*), & Q_{21} = 0 \\ c_2^*, & Q_{21} > 0 \end{cases}$ $\alpha_2 = 0$, $\beta_1 = a_2 - \beta_2$
$Q_1^* > 0$	$\alpha_1 = \begin{cases} \min(a_1, c_1^*), & Q_{11} = 0 \\ c_1^*, & Q_{11} > 0 \end{cases}$, $\beta_2 = a_2$ $\alpha_2 = a_1 - \alpha_1$, $\beta_2 = 0$	$\alpha_1 = \begin{cases} \left(\dfrac{\frac{1}{c_2^*}}{\frac{1}{c_1^*} + \frac{1}{c_2^*}} + \dfrac{Q_2^* - Q_1^*}{\frac{a_1}{c_1^*} + \frac{a_1}{c_2^*}} \right) \cdot a_1, & a_1 > 0 \\ 0, & a_1 = 0 \end{cases}$ $\beta_2 = \begin{cases} \left(1 - \left(\dfrac{\frac{1}{c_2^*}}{\frac{1}{c_1^*} + \frac{1}{c_2^*}} + \dfrac{Q_2^* - Q_1^*}{\frac{a_2}{c_1^*} + \frac{a_2}{c_2^*}} \right) \right) \cdot a_2, & a_2 > 0 \\ 0, & a_2 = 0 \end{cases}$ $\alpha_2 = a_1 - \alpha_1$, $\beta_1 = a_2 - \beta_2$
with	$c_1^* = \min(c_{11}, c_{12}, c_{13})$	$c_2^* = \min(c_{21}, c_{22}, c_{23})$

Table 1: *Parameters for controlling approach in the time-continuous model*

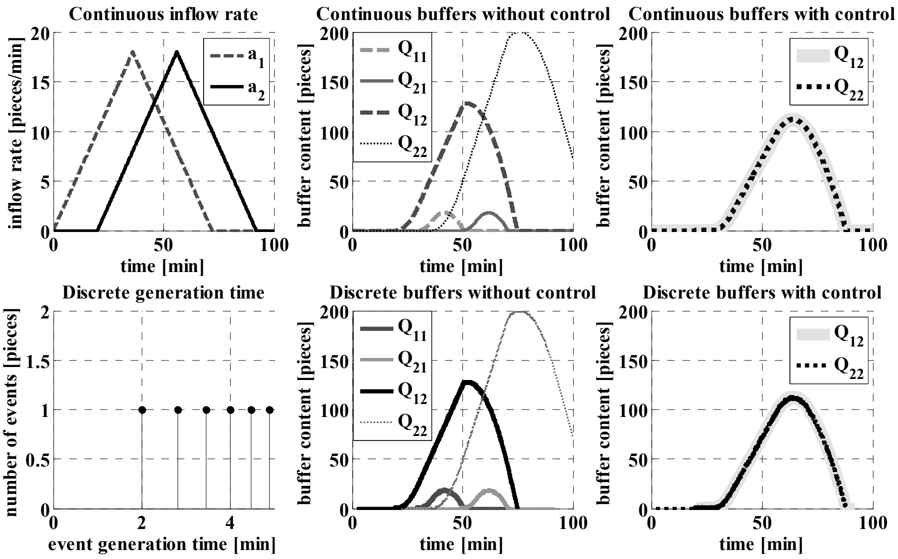

Figure 3: *Simulation results of the time-continuous and discrete event model*

In Figure 3 only buffers with contents greater than zero are shown. The efficiency of the control system can be seen by comparing the result of the buffer contents with and without control. The maximal buffer content is about 40 % lower and the buffers are emptied faster in the controlled situation. The evolution of the buffer queues in both approaches show the same characteristics, so both modeling methods are adequate.

4 Comparison of discrete event and time-continuous model

During application of both modeling methods we identified a set of relevant criteria for picking a suitable approach: qualification of the user, modeling of parts, evaluation during experimentation and computation time (see Tab. 2). Depending on the qualification of the user and on the expectations on the modeled system, applicants can decide which modeling method to use.

Criteria	Time-continuous simulation	Discrete event simulation
Qualification of user	The non-intuitive treatment of the system within the MATLAB environment requires experienced users for formulation and implementation.	Intuitive modeling process and user-friendly simulation programs facilitate the procedure.
Modeling of parts	Modeling of parts in fractions rather than single units due to fluid approximation makes the interpretation of the gained results more complicated. Extended systems with additional production lines or machines are executed fast and efficient.	Individual modeling of parts results in a more instinctive interpretation of the modeling results which is closer to reality. Extended systems with additional production lines or machines are harder to model, the greater they get. However a lot of simulation software provides features for handling complexity.
Evaluation during experimentation	Methods of dynamical systems can be applied, e.g. numerical integration of ordinary differential equations.	Software allows statistical analysis of the model in a competent way. Mean values are often gained.
Computation time	Efficient computation time for high volume of products makes the method attractive for modeling serial production.	Longer computation time for high product volume. In other setups similar to the time-continuous approach.

Table 2: *Comparison of time-continuous and discrete event simulation used in a serial production environment*

5 Conclusion

We presented a new controlling approach for autonomous control in serial production. The enhanced method was implemented in a time-continuous and in a discrete event simulation model to investigate the performance of both methods. A comparison of both approaches as a decision basis for interested users is provided. In further research the controlling approach is extended to integrate the aspect of high variant rates in automotive production as well as other modeling approaches as denoted in section 2 are tested for using.

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