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Autonomous Control in Production Networks under Stochastic Influence

Selbststeuerung in Produktionsnetzen unter Berücksichtigung stochastischer Einflüsse

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Abstract: The scope of this paper is the assessment of inventory reducing autonomous control strategies in serial production networks under stochastic influence. Thereby a flow shop scenario with three production lines including four processors in each case is considered. Three types of products are manufactured, whereas each type is preferably produced on one specific line. In order to maintain validity, a time-continuous approximation of a discrete event simulation model of the flow shop is realized. New methods of feedforward and feedback control as well as a combined strategy are used. After discussing the outcomes of control strategies under deterministic conditions, stochastic effects are added. Implications from deterministic and stochastic realizations are discussed under comparison of their behaviour.

1 Introduction

Companies today are faced with the challenges of decreasing product lifecycles, increasing product diversity, unstable production plans, market globalization and numerous other factors. In such an environment they have to be as flexible and adaptable as the market itself (Nyhuis et al. 2008). This causes turbulences and complexity in production planning and control. In order to induce flexibility and adaptability, production and logistics systems are regarded analogous to physical systems. Similar to implementing control in technical systems for overcoming instabilities and irregular states, new methods for the control of complex dynamics in production and logistics systems are needed (Windt 2006). Plenty of approaches to modelling and controlling the dynamics of production systems have already been developed in the last years (Wiendahl and Breithaupt 2000), whereas pioneering work in this field was published by Forrester (1958). Besides simple push and pull strategies, more sophisticated techniques are regarded as well (van den Berg et al. 2008). However in classical production planning and control systems all flows of parts and processes within the production network are planned ahead by a central planning and control supervisory. In cases of machine failures or absence of material the whole production plan is reorganized, in order to meet the new requirements. The poor degree of flexibility and adaptability which central production planning and control systems show yields in suboptimal performance and low efficiency of the system (Scholz-Reiter et al. 2008, Scholz-Reiter et al. 2007). Per introducing autonomous control to production systems the classical aims of production logistics like minimizing inventory, maximizing throughput or minimizing throughput times (Günther and Tempelmeier 2005) can be achieved. Out of these reasons the benefits of autonomous production planning and control strategies are discussed in recent literature (Scholz-Reiter et al. 2008, Windt et al. 2010a). A majority of considered instruments were developed for the application in job-shop manufacturing since autonomous control in serial flow shop manufacturing is stated as unreasonable due to the solid interlinking of production elements (cf. Scholz-Reiter et al. 2006). Hence, this kind of production is typical for the automotive industry which counts a respectable sector nowadays. Windt et al. (2010b) demonstrate the realization of new autonomously controlled flow shops where the material is able to decide which product variant it becomes. Boyaci and Wenzel (2011) provide new autonomous control policies for the incorporation in an existing serial production system. The scope of this article is to observe the behaviour of these new autonomous control methodologies for a serial production environment under stochastic influences.

In section 2 the considered flow shop scenario is described and the derived autonomous control strategies are shown. Modelling procedures for the discrete event and time-continuous simulation models are provided by section 3. Section 4 demonstrates the simulation results of the presented investigations. Major findings of the presented work and outlines for future aspects are summarized in section 5.

2 Autonomous Control in Production Networks

The autonomous control strategies are performed according to the methods presented in Boyaci and Wenzel (2011). They are derived from an extension of the flow shop scenario described in Boyaci and Wenzel (2010) (cf. Fig. 1).

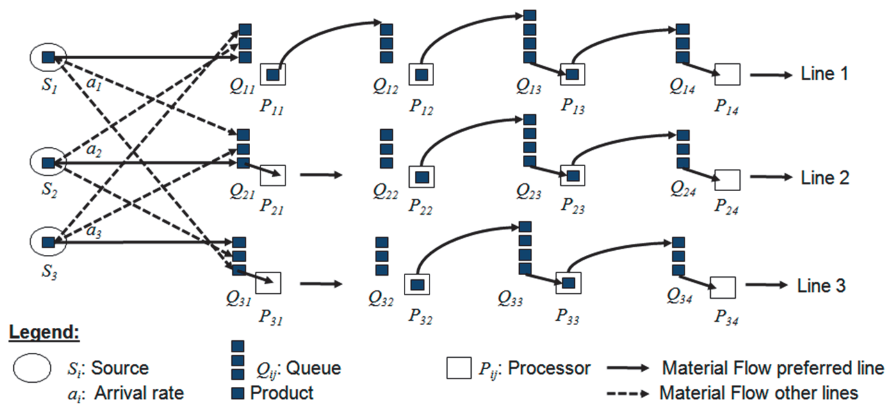

Figure 1: *Flow shop scenario*

The production system consists of three parallel production lines which are organized in the same manner. Parts disembark from the sources S_1, S_2 and S_3 respectively and proceed to one of the three production lines for further treatment. Since we are modelling a serial production, parts do not have the chance to interchange lines, contrary to the scenario assessed by Dashkovski et al. (2006) and Scholz-Reiter et al. (2007). Therefore, once a production line is chosen, parts cannot move to other lines. Furthermore there are no parts gained or lost during the production process. Raw material from the suppliers and buffer capacities of the queues are supposed to be infinite. During the simulation studies setup times are not considered. Within the production system machines do not have any failures or breakdowns. The content of the queues is processed by a FIFO (first-in-first-out) policy. Each production line consists of four processors P_{ij}. In front of every processor exists a queue Q_{ij}. The processors work with capacities c_{ij}. Whereas $i = 1, 2, 3$ mark the indexes of the production lines and $j = 1, 2, 3, 4$ denote the subscripts of processors, queues and capacities of a specific production step.

2.1 Central Routing Policy (CRP)

By application of the first control strategy, all parts out of S_i are directed to production line i with the arrival rate a_i for all $i=1, 2, 3$. These material flows are represented by the solid lines. The demonstrated routing process is equal to a centralized planning. All incoming material is determined prior to its arrival which production line to choose. In the following this method is called Central Routing Policy (CRP).

2.2 Feedforward Control Methodology (FFC)

Parts arriving from the sources S_i, now have the chance to choose a production line of their favour which is represented by the dashed lines in Figure 1. Contrary to Figure 1 let us assume production line 1 to be only capable of producing product types out of S_1. However, production lines 2 and 3 have the ability of producing all product types which occur within the production system. This is a realistic assumption since mutability in manufacturing is only possible to a certain degree. Choice of a suitable production line for each arriving part happens by using a new inventory reducing policy, called Feedforward Control (FFC) in the following. Comparing buffer levels in every production line, parts choose the line with the minimum level to enter. Buffers of the production lines at a certain time step t are represented by:

$$\begin{aligned} Q_1^* &= Q_{11}(t) + Q_{12}(t) + Q_{13}(t) + Q_{14}(t), \\ Q_2^* &= Q_{21}(t) + Q_{22}(t) + Q_{23}(t) + Q_{24}(t), \\ Q_3^* &= Q_{31}(t) + Q_{32}(t) + Q_{33}(t) + Q_{34}(t). \end{aligned} \tag{1}$$

Q_1*, Q_2* and Q_3* denote the sums of buffers in production line 1, 2 and 3, respectively. Since all processors within the production lines are strongly coupled to each other, the outflow location of the parts is determined by their inflow location. On arrival of a part at a production line, two possible situations for each buffer are distinguished. Hence, either condition $Q_1^* = 0$ or $Q_1^* > 0$ is fulfilled. If all buffers in the production line are empty at the same time, then all parts proceed to their preferred production line. For all other cases, the control parameters are determined by the situation of the buffer contents. Production line 1 which is only capable of producing parts out of S_1, is fed with parts till its capacity is exceeded. Material which arrives at production line 1 in situations where it is working on full capacity is directed to the other production lines.

2.3 Feedback Control Methodology (FBC)

In the next routing policy a proportional-integral controller (PI-controller) for realizing a feedback control is implemented. Thereby a characteristic system's variable is chosen in order to follow a reference signal. By measuring the output variable, a suitable input signal for the system is derived. We will call this methodology feedback control (FBC). Hereby an input variable into the control system which provides the input signal of the controller must be defined. In our system's realization it is given by the arrival rate of parts into the system a_i. Furthermore a control variable must be chosen, in dependence of the desired control object. Since we are aiming the reduction of inventory, our control variable is the total inventory of the production system which is given by:

$$Q^*_{total}(t) = Q^*_1(t) + Q^*_2(t) + Q^*_3(t). \quad (2)$$

In order to control this variable to a desired level, the error term

$$e(t) = Q^*_{total}(t) - 0, \quad (3)$$

is established, whereby the total inventory of the production system is controlled against a zero level. Generally, any variable within the system can be controlled to any value. After defining the necessary parameters, the controller can be implemented. Thereby the adjustment of the input variable is driven by the control parameters K_p for the proportional response and K_i for multiplying the integral term (Philips and Harbor 2000). They help deriving the corrected input signal for the system. Within the described setup, the obtained control parameters are $K_p = 12$ and $K_i = 0.06$. A table with algorithms of the controller can be found in Boyaci and Wenzel (2011).

2.4 Combined Control Strategy (CC)

The last presented control strategy combines FFC with FBC. FFC generates a splitting of the incoming parts onto the three production lines within the production system in order to reduce the inventory by maintaining a better utilization of the processors. Whereas FBC induces a proper arrival profile of the parts for capturing better the capacity of the machines. As both approaches support the reduction of the buffer queue contents within the production system a combination of them promises the best result in diminishing the inventory. After setting up a typical production scenario in serial production, we introduced different control methods. All of them are organized in order to lower the inventory within the manufacturing systems. In the next section we will show two different modelling methods for realizing the demonstrated strategies by conducting computer simulations of the models. By comparing the results in prospect to the arrival profile of the parts, the buffer queue contents and the outflow profile of the parts, all control methods are assessed.

3 Simulation Models

For conducting the simulation studies, the models described in Boyaci and Wenzel (2010) are extended to capture the production scenario presented in section 2. The simultaneous modelling procedure from Boyaci and Wenzel (2010, 2011) is carried on for the analysis of the stochastic influence in this paper. This procedure allows maintaining validity of the models throughout the whole analysis. Furthermore FBC within the discrete event model is realized by using the time-continuous arrival rates, generated by the PI-controller in section 2.3. However the stochastic influence is assessed within the discrete event model. Therefore the parallel enhancement of both models as well as their validity is essential for the analysis of the stochastic influence. First, a time-continuous model consisting of ordinary differential equations is derived. In the second modelling step a discrete event simulation model which is supposed to show the same characteristics as the time-continuous model is composed. In the following, both models will be shortly explained, a more detailed description of the ODE as well as the DES can be found in Boyaci and Wenzel (2010, 2011).

3.1 Ordinary Differential Equations Model (ODE)

Individual processors are modelled by ordinary differential equations. Parts arrive at the processors by an inflow rate P_{ij}^{in}. Within a time-continuous system fractions are processed rather than single parts. Thus, the inflows into the first processors in every line of the production system must be individually defined for every control strategy, described in section 2. Every processor disposes over a certain capacity c_{ij}. This capacity determines the outflow out of the processor P_{ij}^{out}. As soon as the inflow gets greater than the capacity, a queue Q_{ij} in front of the processor arises. The evolution of the buffer queue contents is approximated by a system of coupled ordinary differential equations, given by inflow P_{ij}^{in} into the processor minus outflow P_{ij}^{out} of the processor.

3.2 Discrete Event Model (DES)

The same scenario is implemented as a discrete event simulation model. Thereby the sources where the parts come from, are modelled as entity generators which generate entities upon certain event times e_i with $i=1, 2, 3$. These event times are the conversed arrival rates of the time-continuous model. Entities proceed to the different production lines according to the chosen control strategy. Hereby the routing of the entities is realized by different routing blocks.

4 Stochastic Influence on Simulation Results

In simulation studies of the time-continuous and discrete event model, the behaviour of the control strategies from section 2 is assessed. Thereby main differences in the inflow characteristics of parts into the production system between both models, as well as between the control methodologies are demonstrated. By observing the evolution of the buffer queue contents, attention can be drawn to the inventory reducing effects of the implemented control options. Hereby additional impacts on the outflow times of the parts can be analyzed. Stochastic influence into the system is added by a variation in the interarrival times of parts.

4.1 Inflow into the Production Line

On a closer look on Figure 2, the characteristics of both inflow functions can be compared for CRP and FFC. Hence the upper part of the diagram displays the time-continuous inflow of parts per time interval.

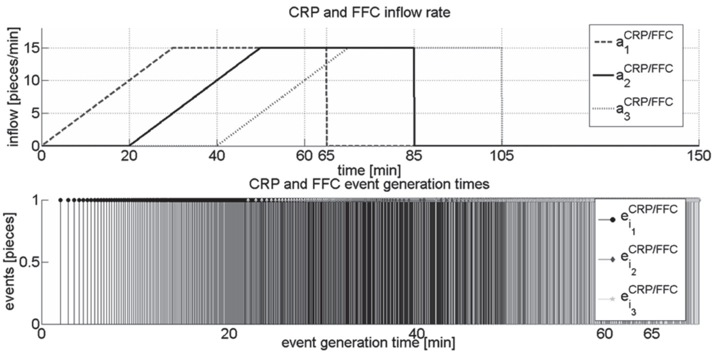

Figure 2: *Inflows time-continuous and discrete event model of control strategies*

Identical input functions a_1, a_2, and a_3 represent inflows into the production lines. They start with a ramping up period, followed by a constant flow, ending with a ramping down interval and are separated by certain time-lags. In order to keep reproducibility between the outcomes of both models, the discrete interarrival times e_{i1}, e_{i2} and e_{i3} of the parts are obtained by integration of the time-continuous input functions a_1, a_2, and a_3 and illustrated in the lower part of Figure 2. During the constant sections of the functions, the input is 15 pieces/min. Capacities of the processors within each production line are given by c_{i1} = 15 pieces/min, c_{i2} = 10 pieces/min, c_{13} = 10 pieces/min, c_{23} = 10 pieces/min, c_{33} = 8 pieces/min, c_{i4} = 15 pieces/min with $i = 1, 2, 3$. Inflow functions can be regarded as a realization of customer orders within the production system. Applying CRP and FFC, customer orders are directly fed into the individual production lines, corresponding to the chosen policy. With FBC the inflow levels are limited on the minimal processor capacity per production line. This effect prevents the building of queues in front of the servers. However, the time the final part enters the system with FBC, lays 35% behind the last arrival with CRP and FFC. Transferred into a real world example, customer orders would be placed later into the production system for maintaining a lower inventory level. Since CC is a combination of FFC and FBC it aggregates the benefits of FFC with those of FBC. Allocation of parts on production lines depends on the total buffer queue contents within the production system. Thus, the characteristics of the inflow are similar to FBC, but slightly differ due to the redirection of parts. Production line 1 gets only as much parts as it can handle without building up a queue. The rest is routed to the other lines. This effect results in a delay of 24% in the arrival time of the final part compared to CRP and FFC. Hence the last entrance into the production system is 8% earlier in time than with FBC. On this account, customer orders can be started earlier by using CC. By adding stochastic behaviour to the inflow functions, the resulting totality of interarrival times with CRP and FFC for production line 2, is given through the histogram in the left part of Figure 3.

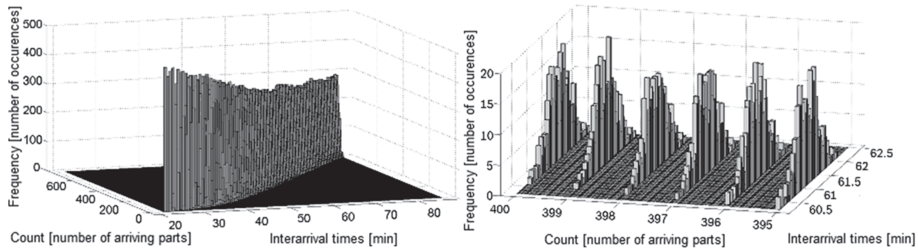

Figure 3: *Interarrival time distributions of Line 2 with CRP and FFC*

We assume an even outflow of the upstream process which varies in a given time frame. Therefore the interarrival times of the parts oscillate around a given mean. This phenomenon is realized by using a normaldistribution which is representing fluctuations around a certain value very well. Thus, the interarrival times are subject to random variation by a normal distribution with mean 0 and a variance of 5%. For variation of the parameters 500 realizations have been conducted. In each experiment a new set of start parameters was generated. On the x-axis the count of parts is mapped. With CRP, 750 parts arrive in total at production line 2. The y-axis displays the distributions of the event generation times depending on the count of the arrived part. The z-axis illustrates the absolute frequency of each event generation time. In a selection of a few interarrival times in the histogram on the right half of Figure 3, the characteristics of the normal distribution can be noticed in the absolute frequency of the event generation times.

4.2 Inventory within the Production System

The inventory per production line is displayed by the characteristic buffer levels Q_i* given in Equation 1. With CRP Q_1* reaches its maximum at 200 pieces whereas the FFC lowers it nearly to zero. This is partly due to the fact that by FFC parts from line 1 can be routed to the other lines but parts from lines 2 and 3 cannot be routed to line 1. FBC and CC manage to bring the buffers in line 1 to a nearly empty level as well. On account of the additional load from line 1 the buffers of FFC increase much more than with CRP in line 2 which is displayed on the left of Figure 4.

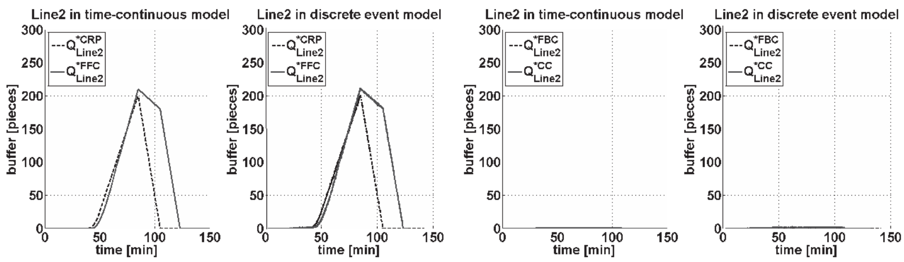

Figure 4: *Buffer in Production Line 2 in time-continuous and discrete event model*

Furthermore they are emptied later with FFC than with CRP which will cause a longer throughput time of the parts. Taking a closer look at the right hand side of Figure 4 we can see that the buffers of line 2 are nearly emptied by applying FBC and CC. Here the success of the PI controller which was designed in order to reduce the buffers within the production system can be seen very clearly. The suitability of the control parameters K_p and K_i is therefore approved. Production line 2 is capable of producing all product types and has the highest capacity. Hence, the most interesting effects of the control strategies can be observed in line 2. Therefore we concentrate in further discussions on this production line. In the following, the behaviour of the buffer queue contents within the production system for the different control strategies under stochastic influence will be examined. Thereby especially the stochastic effects on FFC, FBC and CC, compared to the deterministic outcomes will be interesting. Initially, stochastic influences will be analyzed in the discrete event system. Especially the implementation of the deterministic time-continuous PI-controller from section 2.3 within the discrete event system under stochastic variation will be investigated. Depending on the outcomes, further studies of the time-continuous system under stochastic considerations may be necessary. In Figure 5 the buffers of line 2 under implementation of the different control strategies are visualized.

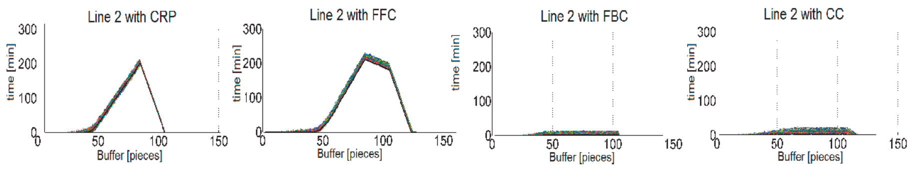

Figure 5: *Buffer under stochastic variation in Line 2*

Thereby the outcomes for all 500 realizations of the simulation experiments are plotted in the four displayed diagrams. The mean of the buffers with CRP in the upper left part of Figure 5 and FFC in the upper right part as well as FBC in the lower left and CC in the lower right show the same characteristics as the buffer queues in the deterministic studies. Therefore we have shown that all four control strategies can be used under stochastic variation as well. However, the investigations of the stochastic influence show that the application of a feedback controller which was derived in a deterministic environment is also suitable for stochastic variations. Thus, the developed feedback controller works under consideration of stochastic behaviour. Nevertheless the functionality of the controller was only analyzed for a stochastic variation of the interarrival times with a normal distribution. For examination of stochastic behaviour in systems with differing upstream processes other probability distributions have to be taken into account. In production processes for example the exponential distribution is common for arrival processes. Production line 3 has the maximum characteristic buffer level of 294 with CRP. Since FFC divides the flows between production line 2 and 3 according to their actual buffer state and their capacities, less flow is fed into production line 3 compared to production line 2 with FFC. Thus, the maximum level is lower than with CRP. FBC and CC provide a decrease of the buffers in production line 3 as well. FBC and CC do not prove a great difference concerning the buffer queues within the production system. The benefit of CC is more emphasized in the next section where the outflow profile of the production systems is analyzed.

4.3 Outflow of the produced parts

The outflows o_1, o_2, o_3 of the production lines, corresponding to the throughput rate of a production system, represent leaving times of parts and working rates of production lines. Since production line 3 has the lowest capacity, the last part leaves the system at 141 minutes. By passing parts to line 2 which has a higher capacity, the production of line 3 can save 10% time in producing the last part. Line 1 gets only as many parts as it can handle without building queues. Hence, it passes parts to line 2 whenever it seems to get overloaded and its last part can leave the system with FFC 25% earlier in time than with CRP. However, these reductions of lines 1 and 3 are paid by 20% longer time till the last part of line 2 leaves. Since line 2 can handle all types of parts and has a higher capacity than line 3 it seems reasonable to utilize it at full capacity. The departure of the last part of FBC is at the same time as CRP. Thus the parts leave the system simultaneously in FBC as in CRP, but they spend less time within the system. According to Hopp and Spearman (2001) this is not only beneficial in terms of reducing costs by maintaining a lower inventory within the production system. It is also an advantage in case of changes in the orders of the customer or by downtime of machines in the production system. Changes of the outside parameters of the production system can be responded better the later orders are realized. The last part of line 3 leaves the system with CC 8% earlier in time than with FBC.

5 Conclusion and Outlook

We have shown four different control strategies for a serial production environment with different product variants. Besides, a central routing policy, feedforward and feedback control as well as a combined strategy of both approaches were implemented. A time-continuous and a discrete event simulation model of a realistic production scenario were used for their evaluation. We investigated changes in the inflow rate, the inventory level and throughput times in the production system in dependency of the derived policies. By comparing metrics of all strategies, CC performs best within the modelled environment. Besides reduced inventory in the production system, the departure time of the last produced part could be lowered in contrast to CRP and FBC. However, the departure time of the last piece is lower in FFC than in CC since the parts can be better allocated between the different production lines. Along with deterministic studies, stochastic effects have been added to the analysis. In varying interarrival times of the parts for all production lines, distributions for all event generation times have been derived in 500 realizations. Thereby a normal distribution with mean 0 and a variation of 5% has been used. We illustrated the influence of stochastics on the behaviour of the buffer queue contents by applying different control strategies. All four methodologies resulted in varied buffer queues with the same mean as in the deterministic studies. Therefore the functionality of the control policies within a stochastic environment under assumption of an even upstream process by variation of interarrival times with a normal distribution was approved. In further research a higher load and higher numbers of different product variants can be taken into account. Moreover, the manufacturing system can be extended. Instead of controlling inventory levels the demand or throughput rate can be controlled. Furthermore the stochastic variation can be extended to general upstream processes by using different distributions.

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