Modelling Autonomous Control in Production Logistics

Bernd Scholz-Reiter
Bremen Institute of Industrial Technology and Applied Work Science (BIBA)
Hochschulring 20, 28359 Bremen, Germany
Phone: + 49 421 218 5576, fax: + 49 421 218 5640
E-Mail: bsr@biba.uni-bremen.de

Thomas Jagalski
Bremen Institute of Industrial Technology and Applied Work Science (BIBA)
Hochschulring 20, 28359 Bremen, Germany
Phone: + 49 421 218 9786, fax: + 49 421 218 5597
E-Mail: jag@biba.uni-bremen.de

Summary

This paper gives an overview of the modelling of autonomous control strategies for production logistics. First, a general and universal shop floor scenario with and without setup times is presented. After that, several autonomous control strategies are discussed. Modelling details, i.e. the machines' service rule, the equivalent of an autonomous decision, a pheromone-based concept with an evaporating pheromone concentration etc. are presented. Based on the simulation results the logistics performance as well as the influence on the system's behaviour is assessed.

Keywords

Autonomous control strategies, production logistics, logistics performance

1 Introduction

Due to increasing market dynamics, Production Planning and Control (PPC) has become more challenging for manufacturing companies. Production plans have to adapt quickly to changing market demands. Conventional PPC methods cannot handle unpredictable events and disturbances in a satisfactory manner because in practice the complexity of centralised architectures tends to grow rapidly with size, resulting in rapid deterioration of fault tolerance, adaptability and flexibility [KD04]. To manage the increasing dynamics inside and outside a production system, a decentralized and autonomous control of shop floor logistics is a promising approach [SWF04]. In the context of engineering science, the global definition of autonomous control [HW07] is adapted: “Autonomous Control in logistic systems is characterised by the ability of logistic objects to process information, to render and to execute decisions on their own” [SWF04]. In other words, in decentralized and autonomous control strategies autonomous elements are able to make decisions by themselves using distributed local information. Thus, the concept of autonomous control requires on one hand logistic objects that are able to receive local information, process this information, and make a decision about their next action. On the other hand, the logistic structure has to provide distributed information about local states and different alternatives to enable decisions generally.

Recent information and communication technologies, such as radio frequency identification (RFID), wireless communication networks etc., enable intelligent and autonomous parts and products, which are able to communicate with each other and with their resources, i.e. machines and transport systems etc., and to process the acquired information. This leads to a coalescence of material flow and information flow and enables every item or product to manage and control its manufacturing process autonomously [SWF04]. RFID-equipped parts may for example use data about predecessors, which is collected with the help of RFID-readers, in order to render their decisions in a pheromone-based control strategy.

To develop and benchmark autonomous control strategies, dynamic models are essential. Furthermore, one has to consider both, the local decision-making processes and the global behaviour of the system. The interactions and interdependencies between local and global behaviour are not trivial. In a colony of ants for ex-ample a single ant has no idea about the whole colony and its actions are based on a few simple rules. On the other hand, the entire colony consisting of thousands of ants is able to build gigantic nests, to find shortest paths between food and nest etc. This self-organisation is a so-called emergent behaviour of a complex dynamic system and not derivable from single characteristics [P974, UMM+01].

In the following, exemplary scenarios of a shop floor, several autonomous control strategies as well as implementations with the help of continuous System Dynamics simulation models are presented. Thus, one goal of this contribution is to offer an overview of the autonomous control strategies for production logistics recently developed by the authors. The main focus lies on the comparison of the effects of the different autonomous control strategies on the logistics performance of the system and its behaviour.

2 Exemplary Scenarios

The considered shop floor is a matrix-like flow-line manufacturing system producing k different products at the same time. Each of the products has to undergo m production stages. For each of these production stages there are n parallel production lines available. Therefore, the shop floor consists of mxn machines. The raw materials for each product enter the system via sources and the final products leave the system via drains. The production lines are coupled at every stage and every line is able to process every type of product within a certain stage. At each production stage a part has to make an autonomous decision to which of the lines to go to in the next stage. Each machine has an input buffer in front, containing items of the k product types. The arrival rates are chosen to simulate a varying seasonal demand for the different product types. Thus, the arrival functions for the three product types are defined as sine functions. They are identical except for a phase shift of 1/k period (for the topology, see Image 1 and cf. [SFB+05a, SFB+05b]). This scenario was chosen because of its general and universal character, it can be applied to the majority of real world shop floor configurations. Additionally, it is assumed that different product lines are more suitable for certain products. This can be done by setup times or by differing processing times.

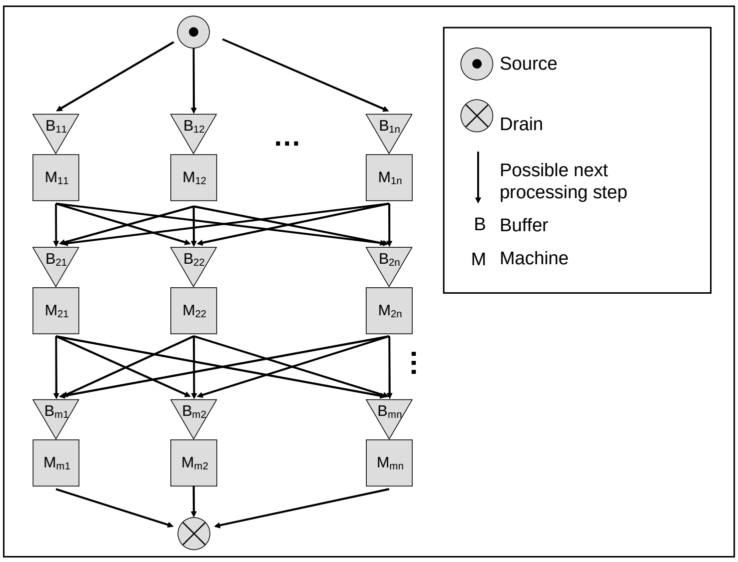

Image 1: Universal mxn shop floor scenario

In this context, the machines' service rule for the different product types is important, e.g. it may be first in - first out (FIFO) for scenarios with different processing times and without setup times and has to be adapted to a rule that considers the current setup status in scenarios with setup times. In the following, different autonomous control strategies for these scenarios with both, different processing times and different setup times will be presented. To analyze the system's behaviour the logistics performance is benchmarked. Three exemplary criteria of logistics performance in production systems are presented: the throughput times, the buffer levels at one production stage and the inventory levels (aggregated buffer levels).

3 Autonomous control strategies

Different autonomous control strategies can be distinguished by the information they use in the decision making process: rational strategies may rely on information about the current situation and a prediction of a future situation of the system (expected values) or on information about how good alternatives had been in the past (experience of the predecessors) or on both.

3.1 The queue length estimator

The queue length estimator (QLE) [SFB+05a, SFB+05b] is an autonomous control strategy that lets a part compare actual buffer levels of the different alternatives (all parallel machines) that are able to perform its next production step. In this case, the buffer levels are calculated as the sum of the estimated processing times of the waiting parts in the respective buffer on the respective machine plus its own expected processing time. When a part has to render the decision about its next processing step it compares the current buffer levels, i.e. the estimated waiting time until processing, and chooses the buffer with the shortest waiting time. Thus, the QLE uses the available information to predict the systems future state. It is suitable for scenarios with different processing times and with setup times.

3.2 The pheromone-based autonomous control strategy

The pheromone-based autonomous control strategy [ABB+06, SDZ+06, SJB+07] uses data from past events. Every time a part leaves a machine, i.e. after each processing step, the part leaves information about the duration of its processing and waiting time at the respective machine. The following parts use these data to render their decisions. Thus, the parts' decisions are based on backward propagated information about the throughput times of finished parts for different routes. Routes with shorter throughput times attract parts to use these routes again. This process can be compared to ants leaving pheromones on their way to communicate with following ants. As in other pheromone concepts [BDT99, PBV+99], the communication takes place indirectly by changing the environment. This pheromone-based autonomous control strategy differs from approaches from ant colony optimization (ACO, e.g. [BDT99]) since there is no self-reinforcing guided search process for optimal solutions. The pheromone-based autonomous control strategy can be used for scenarios with different processing times. However, in a pheromone-based concept, setup times are somewhat hard to handle because predecessors' decisions have influence on successors, which is ordinary not communicated by the pheromone. This can be solved by the introduction of a correction term for the pheromone concentration [SJB+07].

3.3 Mixed strategy

The QLE and the pheromone-based autonomous control strategy can be combined to a mixed strategy [SJB+07] that incorporates a weighted combination of the prediction of the future state of the system and the experience of predecessors. This strategy can be used for scenarios with different processing times and setup times.

4 Modelling details and simulation results

A sophisticated System Dynamics model of the shop floor scenario (cf. chapter 2) has been set up with the help of the System Dynamics Software Vensim by Ventana Systems, Inc. With this model different scenarios can be analyzed by altering the decision making process as well as parameter values. The System Dynamics approach was chosen in order to simulate continuous flow models of production systems. Here the term continuous denotes the continuous material flow, which differs from the flow of discrete parts in e.g. a discrete event simulation model. In literature, continuous flow models of production systems are often called hybrid models [CSR93, PWP+046]. That means the material flow is modelled as continuous flow which is controlled by discrete actions; such a discrete control is typical for production systems. In order to handle the complexity, the simulation models are reduced to 3x3 machines producing 3 different products. Within a given period of time (30 days; cf. x-axis 'Simulation Time') the arrival functions for the three product types are defined as sine functions to simulate seasonal varying demand. They are identical except for a phase shift $\varphi = 1/3$ period. Due to a usual workload of about 80 % in real production systems, a mean arrival rate λ_m

= *0.4 1/h* and an amplitude of the sine functions of *α* = *0.15 1/h* are chosen, meaning that on average every 2:24 h a new part of product type A, B and C arrives to the system. Image 2 shows the three arrival rates (y-axis) over the simulation time.

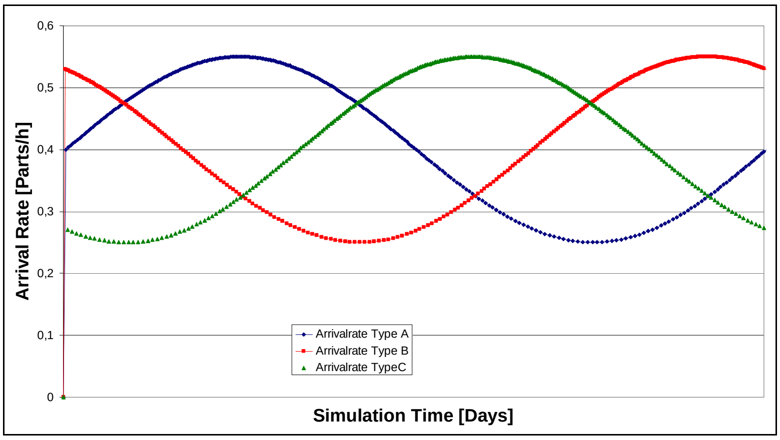

Image 2: Arrival rates for the 3x3 shop floor simulation model

4.1 Scenario 1 – No line switching, different processing times, no setups

It is assumed that each machine at each stage has different processing times for each product as they are shown in Table 1.

Table 1: Processing times of the 3x3 machines model

Product type	Processing times [h:min] at production line		
	1	2	3
Type A	2:00	2:30	3:00
Type B	3:00	2:00	2:30
Type C	2:30	3:00	2:00

When prohibiting line switching, each part is directed to its preferred production line. This can be interpreted as a central and preplanned control in PPC, depicting a scenario, in which the seasonal varying demand could not be forecasted. To analyze the logistics performance of this system, the throughput times (TPT) for the three different part types are examined. They are calculated in real-time with the help of Little’s Law [SFB+05a]. Image 3 shows the TPT (cf. y-axis) for this scenario (maximum throughput time of 19:48 h and mean throughput time is 9:55 h with a standard deviation of 5:08 h) within the regarded simulation period of 30 days (cf. x-axis). As could be expected, the parts just pile up in the buffers during periods of overload. When the arrival rate drops below 0.5 1/h, the buffer levels and the waiting times decline to the minimum throughput time of 6 h. Because of the identical arrival functions for each part type, the time series of the throughput times have the same shape with a phase shift of 1/3 period.

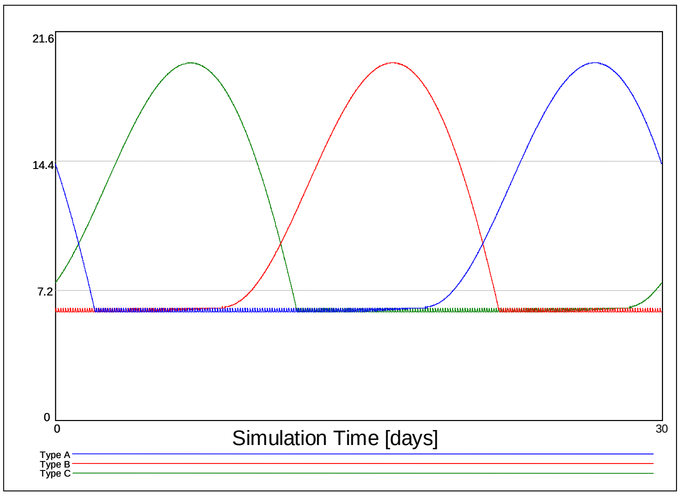

Image 3: Throughput times for the three different part types in case of preplanning and without setup times but with different processing times

4.2 Scenario 2 – QLE, different processing times, no setups

Each machine at each stage has different processing times for each product (see Table 1). The part chooses the buffer with the lowest expected waiting time. Again, the throughput times for the three different part types are examined. Image 4 shows the throughput times for this scenario. Image 4 shows that the logistics performance is significantly better as in scenario 1: The maximum throughput time (cf. y-axis) is reduced by 26 % to 14:42 h and the mean throughput time by 18 % to 8:07 h with a standard deviation of 2:14 h).

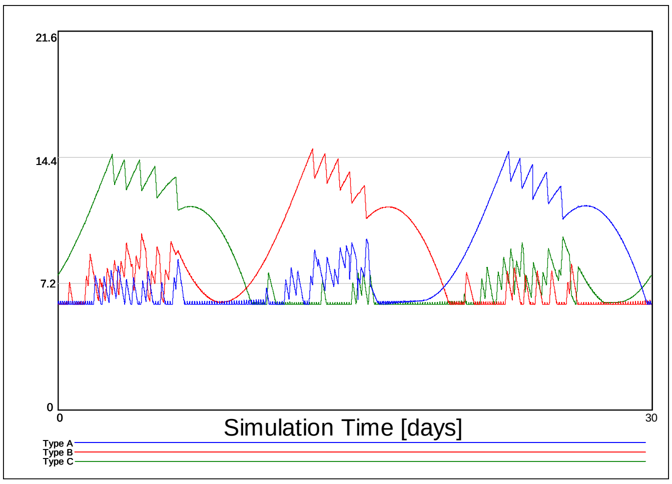

Image 4: Throughput times for the three different part types with QLE in the case without setup times but with different processing times

4.3 Scenario 3 – Pheromone-based autonomous control strategy, different processing times, no setups

In this scenario it is again assumed that each machine at each stage has different processing times for each product (see Table 1). The pheromone concentration is updated every time a part has been processed. Additionally, the concentration is diminished by an 'evaporation constant', which ensures an exponential decay of the amount of pheromone – the equivalent to an evaporation process. This is different from modelling with a discrete event simulator that relies on a moving average of the last parts to implement a pheromone-based approach [ABB+06].

The pheromone concentration update algorithm works as follows: Let $P_{mnk}(t)$ denote the pheromone concentration for machine mn at time t, E_{mnk} the evaporation constant ($0 < E_{mnk} << 1$) for product type k at machine mn, β_{mnk} a (constant) adjustment factor for the pheromone concentration update for product type k at machine mn and $TPT_{mnk}(t)$ the actual throughput time for product type k at machine mn. Then the pheromone updating process is given by:

$$P_{mnk}(t) = P_{mnk}(t) - P_{mnk}(t-1) * E_{mnk} + \begin{cases} \beta_{mnk} * TPT_{mnk}(t), if \text{ 'machine has completed its job'} = true \\ 0, else \end{cases} \tag{1}$$

To evaluate the system's performance (cf. Image 5), the buffer levels for the three buffers of the first production stage (cf. y-axis) are examined (maximum 8.26 pieces, mean buffer level is 3 pieces with a standard deviation of 3.05 pieces).

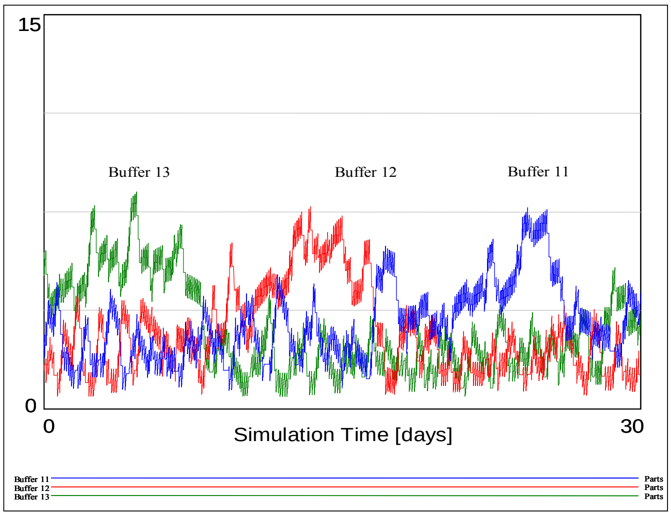

Image 5: Buffer levels of the first production stage with pheromone-based strategy, without setups but with different processing times

4.4 Scenario 4a – Pheromone-based strategy with setups

It is assumed that the processing times for each product are the same: 120 minutes and that set-up times have to be taken into account (cf. Table 2).

Table 2: Setup times of the 3x3 machines model

Set-up times [min]	**Machine** M_{m1}	M_{m2}	M_{m3}
A -> B	30	10	60
A -> C	60	30	10
B -> A	10	60	30
B -> C	60	30	10
C -> A	10	60	30
C -> B	30	10	60

When implementing the pheromone-concept as in scenario 3 (cf. Equation 1), it does not perform in a satisfactory manner (maximum inventory is 13.86 pieces and the mean inventory is 8.65 pieces with a standard deviation of 6.11 pieces; cf. Image 6). Here, the inventory (cf. y-axis) was chosen as a criterion for the logistics performance of the system. It can be calculated by the aggregation of the buffer levels for example at the first production step.

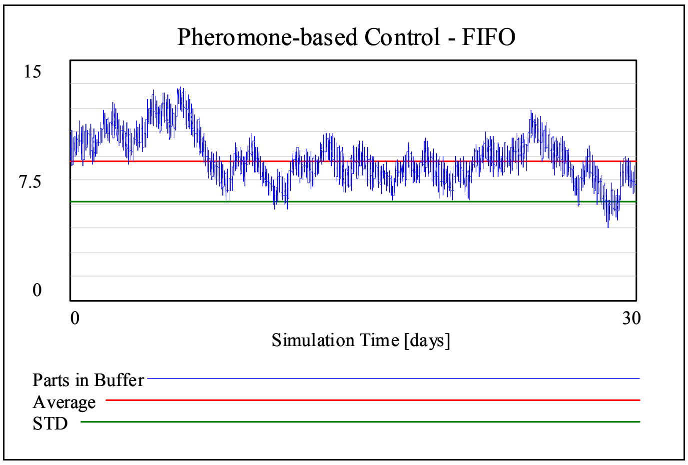

Image 6: Aggregate buffer levels (inventory) of the first production step with pheromone-based autonomous control in a scenario with setup times

There are two main reasons why this performance seems to be improvable: The pheromone concentration does not include information about the set-up status of the machine, and a part's decision can be both, good or bad, depending on how many set-ups the machine has to perform before the part can be processed. The second reason is not included in the pheromone concentration either. Thus, the machines' service rule has to be improved and a correction term for the pheromone concentration has to be implemented.

4.5 Scenario 4b – Improved pheromone-based strategy with correction term, with adapted machines' service rule, with setups

In scenario 4b the arrangement does not change but the pheromone-based autonomous control strategy is adapted and the machines' service rule is improved. A service rule, which enables the machines to select autonomously, which part to process next, is implemented. This can easily be done letting the machines try first to empty the buffer of parts of the same product type. The update process of the pheromone concentration of scenario 3 has to be altered: a correction term is introduced. This correction term includes information about the product type a machine is setup to after a part has been processed. This can not be done by simply leaving a higher amount of the pheromone because this additional information should effect a direct successor's decision only. A higher pheromone quantity would evaporate over time according to the evaporation constant leading to bad information for the next but ones' decisions. Thus, the correction term consists of an additional amount of pheromone with a higher evaporation constant. The pheromone update algorithm works as follows: Let $CT_{mnk}(t)$ denote the value of the correction term for product type k at machine mn at time t, δ_{mnk} a constant adjusted to the execution time for product type k at machine mn, EC_{mnk} the evaporation constant for the correction term (1 > EC >> E) for product type k at machine mn and $set\text{-}up\_status_{mn}(t)$ the status the machine mn is actually set-up to. Then, the pheromone concentration with correction term $P\_cor_{mnk}(t)$ consists of the pheromone part $P\_part_{mnk}(t)$ and the correction term part $CT_{mnk}(t)$:

$$
\begin{aligned}
&P\_cor_{mnk}(t) = P\_part_{mnk}(t) + CT_{mnk}(t) \\
&with \\
&P\_part_{mnk}(t) = P\_part_{mnk}(t) - P\_part_{mnk}(t-1) * E_{mnk} \\
&+\begin{cases} \beta_{mnk} * TPT_{mnk}(t), if \ \text{'machine has completed its job'} = true \\ 0, else \end{cases} \\
&and \\
&CT_{mnk}(t) = CT_{mnk}(t) - CT_{mnk}(t-1) * EC_{mnk} \\
&+\begin{cases} \delta_{mnk}, if \ set-up\_status_{mnk}(t) = k \\ 0, else \end{cases}
\end{aligned}
\qquad (2)
$$

Adjusting the higher evaporation constant for the correction term EC_{mnk} to the execution time (processing time plus set-up time) of the next part on a particular machine, the improved pheromone-based autonomous control strategy should perform better. Image 7 shows the aggregate buffer levels (cf. y-axis) of the first production step.

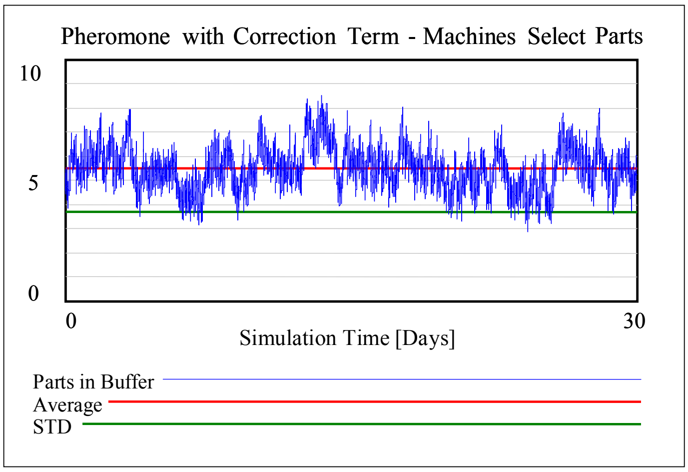

Image 7: Inventory of the first production stage with improved pheromone strategy, with correction term and with adapted machines' service rule

The performance is improved compared to scenario 4a: The maximum inventory level is reduced to 8.55, the mean inventory level to 5.51 and the standard deviation to 3.67 pieces.

4.6 Scenario 4c – Mixed strategy in a scenario with setup times

In scenario 4c the setup does not change but a different and more sophisticated autonomous control strategy is implemented. The queue length estimator, as it was shown in scenario 2 is combined with the improved pheromone-based autonomous control strategy with a correction term and with adapted machines' service rule from scenario 4b (cf. Equation 2). The result is a mixed autonomous control strategy that incorporates a weighted combination of the prediction of the future state of the system and the experience of predecessors. Both methods have shown their performance capabilities in different scenarios [8, 9, 10, 11]. On the other hand, their degree of logistic goals achieved differs in scenarios with rising structural complexity. The pheromone strategy shows a diminishing degree and the QLE a more or less constant degree of logistic goals achieved when the structural complexity rises [SFB+06]. The performance of this new autonomous control strategy (see Image 8; cf. inventory on the y-axis) is excellent. The maximum inventory level is reduced to 8.21 and the mean inventory level to 5.44 pieces with a standard deviation of only 3.55 pieces. At this point it is remarkable that the time it took to simulate this scenario on a standard Pentium 4 computer did not rise significantly compared to the simpler strategies described above – in all cases the simulations took less than two minutes.

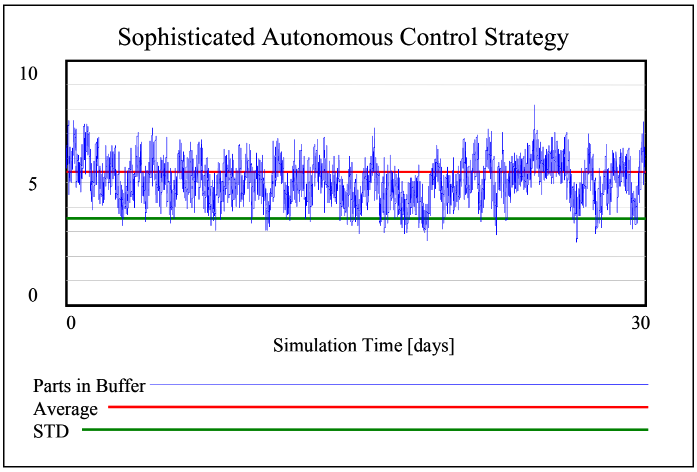

Image 8: Inventory of the first production stage with mixed autonomous control strategy in a scenario with setup times

5 Conclusion

Different general and universal scenarios of shop floors with and without setup times and with and without different processing times have been presented. In a second step, the effects of the different autonomous control strategies on the logistics performance of the system and its behaviour have been analyzed. Several modelling details, i.e. the machines' service rule, the equivalent of an autonomous decision, the evaporating pheromone concentration, the implementation of the necessary correction term to the pheromone concentration in scenarios with different setup times etc. were explained. With that, an overview of modelling autonomous control strategies for production logistics has been presented. The analysis of the performance and behaviour of the different autonomous control strategies has shown that designing a mixed strategy, which incorporates a weighted combination of the prediction of the future state of the system and the experience of predecessors, is promising. The presented mixed strategy outperformed the simpler strategies. Future research would comprehend the design of (mixed) autonomous control strategies according to scenarios with different levels of complexity.

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Prof. Dr.-Ing. Bernd Scholz-Reiter

Prof. Scholz-Reiter served as post-doctorate fellow researcher at IBM T. J. Watson Research Center in New York, U.S.A. in the department of Manufacturing Research from 1990 to 1991. There he was involved in the development of an integrated data model for a series of planning and simulation systems in manufacturing.

From 1994 to 2000 he served as full professor in the department of Industrial Information Systems at the newly founded Brandenburg Technical University at Cottbus, Germany. Simultaneously, he was head of the Fraunhofer Application Center for Logistics Systems Planning and Information Systems at Cottbus, Germany.

Since November 2000 he is a full professor in the department of Planning and Control of Production Systems at the University of Bremen and also serves as Director of the Bremen Institute of Industrial Technology and Applied Work Science (BIBA) at the University of Bremen, Germany.

Prof. Scholz-Reiter is a member of the Berlin-Brandenburg Academy of Sciences, a member of acatech, a union of all national Academies of Sciences with experts from both academia and industry, he is a corresponding member of CIRP, the International Acadeny for Production Engineering, an Advisory Board member of the Schlesinger Laboratory at TECHNION - Israel Institute of Technology, Haifa, Israel.

He is also a member of the Senate Committee for Affairs of Collaborative Research Centres and a member of the Senate Decision Committee for Funding of Collaborative Research Centres of the Deutsche Forschungsgemeinschaft.

Prof. Scholz-Reiter is chairman of the International Graduate School for Dynamics in Logistics at the University Bremen.

Prof. Scholz-Reiter is Editor of the professional journals Industrie Management und PPS Management.

Thomas Jagalski, M.Sc.

Thomas Jagalski has achieved his Masters degree in Economics and in Management at the Humboldt University in Berlin in 2003. He is now working on his PHD in Planning and Control of Production Systems.