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Modelling Dynamics of Autonomous Logistic Processes: Discrete-event versus Continuous Approaches

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Abstract
For developing and benchmarking autonomous logistic processes, dynamic models are essential. The paper investigates two different modelling approaches regarding their abilities to describe an exemplary scenario – an autonomously controlled shop floor. A discrete-event simulation model is compared to a continuous System Dynamics model. An autonomous control strategy is developed and its effectiveness and robustness are investigated by analysing the dynamic behaviour and the logistic performance in cases of work load fluctuations and unexpected disturbances.

Keywords:
Production, Control, Autonomy

1 INTRODUCTION

Due to increasing market dynamics, Production Planning and Control (PPC) has become more challenging for manufacturing companies. Today, production plans have to adapt quickly to changing market demands while conventional PPC methods cannot handle unpredictable events and disturbances in a satisfactory manner [1].

To manage these dynamics inside and outside a production system, autonomous control strategies are a promising approach [2]. Here autonomous control means a decentralised coordination of intelligent logistic objects (parts, machines etc.) and the routing through a logistic system by the intelligent parts themselves.

This 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.

For developing and benchmarking such autonomous control strategies the local decision-making processes as well as the global behaviour of the system have to be considered. Thereby the interactions and interdependencies between local and global behaviour are not trivial. Remember a colony of ants where a single ant has no idea about the whole colony. It only acts by a few simple rules but 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 [3] [4].

Such interdependencies between local and global behaviour may play an important role in developing and benchmarking autonomous control strategies for logistic processes. To capture and describe this situation a dynamic model of the considered logistic process is essential. But due to the unusual requirements to the model, some questions appear: Which level of abstraction does one have to consider? Is it possible to capture both micro- and macro-dynamics in one model? What are appropriate modelling approaches to deal with? Are common modelling tools able to meet the unusual requirements? The paper will try to answer some of these questions by presenting first results about modelling dynamics of autonomous logistic processes.

In the following, two different modelling approaches are investigated regarding their abilities to describe an exemplary scenario – an autonomously controlled shop floor. A discrete-event simulation (DES) model is compared to a continuous System Dynamics model. Here the term continuous denotes the continuous material flow in comparison to the flow of discrete lots in the DES model. In literature, continuous flow models of production systems are often called hybrid models [5] [6]. That means the material flow is modelled as continuous flow which is controlled by discrete actions. This discrete control is typical for production systems and is applied here in both the continuous and the discrete model.

These dynamic models are used for developing autonomous control strategies. Their effectiveness and robustness are investigated by analysing the dynamic behaviour and the logistic performance in cases of work load fluctuations and unexpected disturbances.

2 SHOP FLOOR SCENARIO

The considered shop floor consists of n parallel production lines each with m machines M_{ij} and an input buffer B_{ij} in front of each machine (see Figure 1). Every line processes a certain kind of product A, B, … X by m job steps. The raw materials for each product enter the system via sources; the final products leave the system via drains.

In this shop floor, two different logistic control situations will be compared. In the first case, each line processes its associated product independently from the other lines. Here, the way of the single lots through the machines is pre-determined by a hierarchical planning process.

In the second case, the production lines are coupled at every stage. Furthermore, every line is able to process every kind of lot at the machines within a certain stage. This structure allows a lot to switch between lines at every stage. The decision about changing the line is made by the lot itself on the basis of local information about buffer levels and expected waiting times until processing. Additionally, the lots take into account that the processing times are higher on foreign lines than on their own.

This logistic strategy will be called autonomous control because the lots are autonomous in their decision and there is no superior controller who decides in which way the lots will be processed [7].

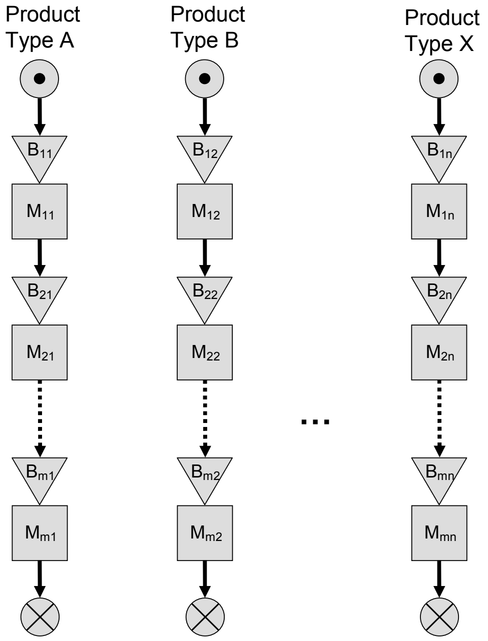

Figure 1: mxn machines shop floor scenario.

In the following the impact of autonomous control strategies on dynamics and performance of the described shop floor will be investigated. For that, two different modelling approaches are used: the discrete-event simulation based on a queuing network and a System Dynamics model based on differential equations.

3 DISCRETE-EVENT SIMULATION MODEL

To handle the complexity of the shop floor the described scenario is reduced to 3x3 machines, i.e. three production lines each with three stages. This structure is modelled using a discrete-event simulation software tool.

To analyse the system's behaviour at workload fluctuations the arrival function is defined as a sine function as shown in Figure 2. Here the interarrival times are plotted against the simulation time for one simulation period. The arrival functions for the three product types are identical except for the phase shift of 1/3 period. Note that a higher interarrival time indicates a lower workload and vice versa. The interarrival times oscillate around a mean value of 2:24 h which indicates a mean workload of 80 % in the first case of independent production lines.

The successive processing times for one kind of lot at the different machines in one line are equal due to the usual balance condition. But because of the possibility of line changing, one has to consider processing times for every lot type at every line (see Table 1). The lots have the lowest processing times on their own line and have higher processing times if they change the line. At each production stage the lots compare the future processing times of the lots in the buffers and choose the machine with the minimal waiting time to be processed on.

Figure 3 shows the throughput times for the three different product types in the first case of independent lines. Because of the identical arrival functions for each lot type, the time series of the throughput times have the same shape. For all three lot types the maximum throughput time in this case is 19:48 h and the mean throughput time is 9:55 h with a standard deviation of 5:08 h (see Table 2).

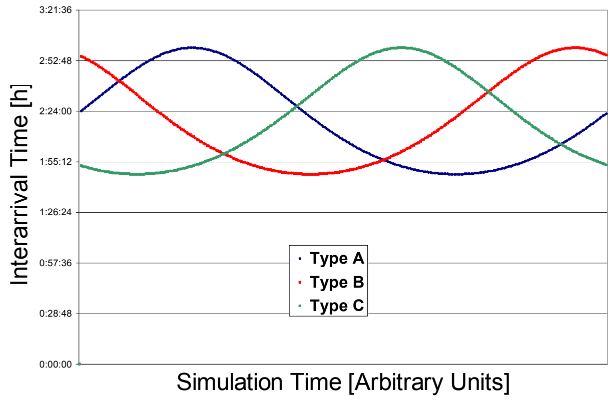

Figure 2: Interarrival times during one simulation period.

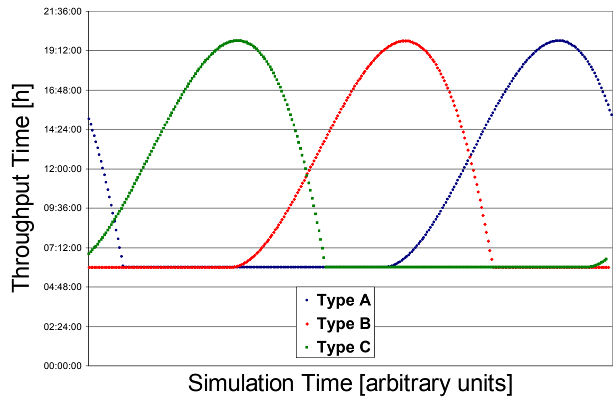

Figure 3: Throughput times in case of independent lines, DES model.

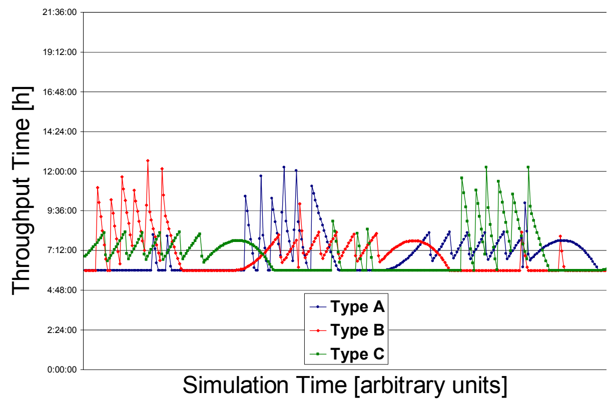

Figure 4: Throughput times in case of autonomous control, DES model.

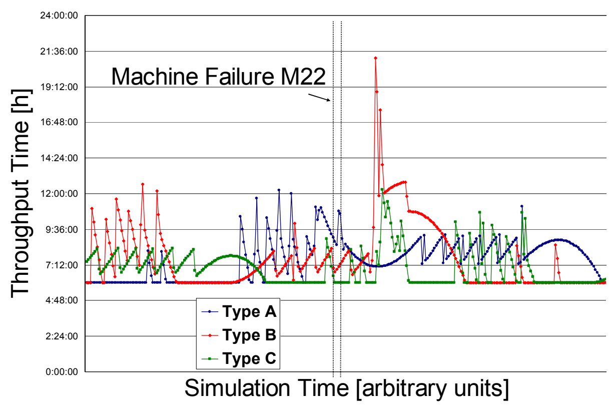

Figure 5: Throughput times in case of autonomous control and machine failure, DES model.

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Lot/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

Table 1: Processing times of the 3x3 machines model.

For the second case of autonomous line switching, Figure 4 shows the time series of throughput times for the three different product types. Again identical shaped time series of the throughput times of each lot type are observed but the maximum and the mean throughput times have been significantly reduced. Obviously, this effect occurs because in case of capacity overload the lots switch to other lines even if the processing time is higher there. In this second case the maximum throughput time is reduced by 36 % to 12:38 h and the mean throughput time is reduced by 30 % to 6:56 h with a standard deviation of only 1:13 h (see Table 2).

To analyse the robustness of the autonomously controlled shop floor a machine failure at machine M_{22} and a downtime for 12 h is modelled. In case of independent production lines the lots on line 2 are stored in the buffer B_{22} until the machine is recovered and the mean throughput time for lots of type B rises to 13:22 h while the other lines are unaffected.

Figure 5 shows the throughput times for autonomously switching lots. One can see the sudden rise of the throughput time of lot type B which reaches a maximum of 21:07 h but this high throughput time is quickly reduced and again the lots are distributed between the lines. In this case the mean throughput time for lots of type B rises to 7:37 h with a standard deviation of 2:13 h (see Table 2) while the mean throughput times for type A rises to 7:34 h respectively to 6:58 h for lots of type C.

Summarising one can say that by introduction of alternative processing capacities and autonomous control strategies based on local information and local decision-making of intelligent lots, the shop floor can adapt itself to changing work loads and can autonomously react to unexpected disturbances. In the presence of high dynamics autonomous control strategies lead to a higher performance of shop floor logistics (see Table 2).

	Min TPT [h:min]	Max TPT [h:min]	Mean TPT [h:min]	SDV TPT [h:min]
Independent lines	6:00	19:48	9:55	5:08
Coupled lines with autonomous control	6:00	12:38	6:56	1:13
Coupled lines with autonomous control and machine failure (only type B)	6:00	21:07	7:37	2:13

Table 2: Performance measures of the discrete-event simulation model.

4 CONTINUOUS SYSTEM DYNAMICS MODEL

The second approach to describe the dynamic behaviour of an autonomous shop floor is done by a continuous System Dynamics model.

To keep the comparability to the discrete-event simulation model the structure of the continuous model is chosen as follows: The arrival of material is modelled as a flow of fragments of lots. A fragment of this flow can be interpreted as work per time unit. The flows A, B and C arrive continuously. A complete lot of type A, B or C respectively arrives at an average of 2:24 h. Analogue to the discrete-event model the continuous model's arrival function is set as a sine function with a mean work load of 80 % (see Figure 2). The raw material comes from a source and enters a buffer of choice instantaneously.

A machine is only able to handle a complete lot at a time but an already processed fragment of a lot can be passed on to the next buffer instantaneously. Therefore, the lots have to be built dynamically within the buffers. The lot type depending processing times at the different machines are again shown in Table 1.

For this model setup, an advanced control mechanism is developed. The autonomous decision about changing the production line is based on two different types of information: Arriving amounts of work decide autonomously not only with respect to the amount of work in a buffer but also with respect to the amount of work of the same type that is already in the buffer. This is necessary because the expected waiting time depends on both the total amount of work in the buffer and the time until the lot of the corresponding type is assembled.

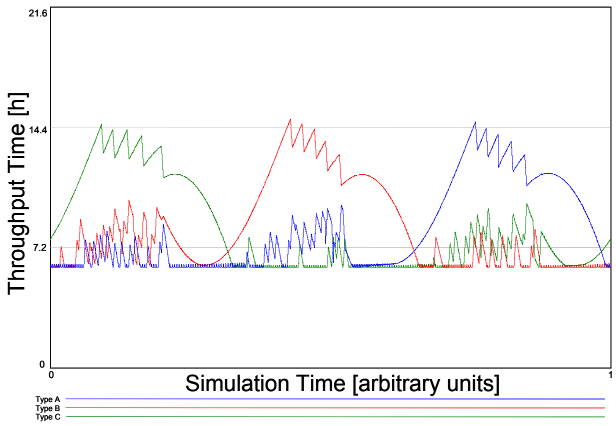

Figure 6: Throughput times in case of autonomous decisions only based on information about the lot size to be reached, continuous model.

Figure 6 shows the throughput times for the three different lot types if the arriving amounts of work make their decisions only based on information about the lot size to be reached, i.e. the amount of work of the same type in the buffer. This is a trivial case because the very first amount of work chooses the first buffer of its own preferred production line and all following amounts of work of the same type will choose the same buffer. Thus, the scenario is equivalent to the first case of the discrete-event model without autonomous line switching (see Figure 3). Again, the time series of throughput times of the products A, B and C have the same shape with a maximum of 19:48 h and a mean of 9:55 h with a standard deviation of 5:08 h (see Table 3).

	Min TPT [h:min]	Max TPT [h:min]	Mean TPT [h:min]	SDV TPT [h:min]
Independent lines	6:00	19:48	9:55	5:08
Coupled lines with autonomous control	6:00	14:42	8:07	2:14
Coupled lines with autonomous control and machine failure (only type B)	6:00	15:06	8:10	2:18

Table 3: Performance measures of the continuous System Dynamics model.

For the second case, the system's behaviour, which is caused by autonomous and simultaneous decisions based on information about the lot sizes to be reached as well as the buffer levels, is analysed. The attractiveness of a low buffer level and a low expected waiting time until a lot is completed are weighted in a manner that the throughput time is minimised. Figure 7 shows that the throughput times for product types A, B and C are significantly lower in mean and deviation. The maximum throughput time 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.

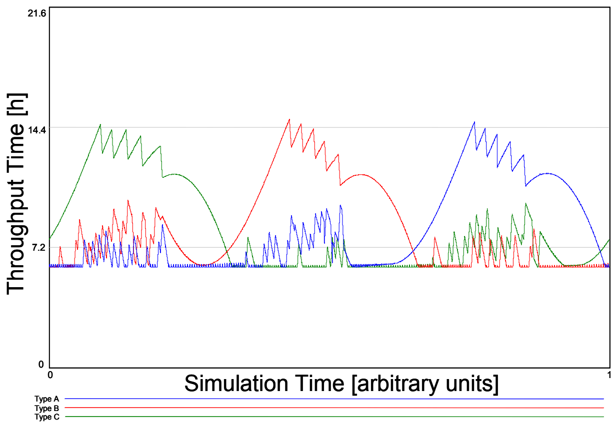

Figure 7: Throughput times in case of autonomous decisions based both on information about the lot sizes to be reached and the buffer levels, continuous model.

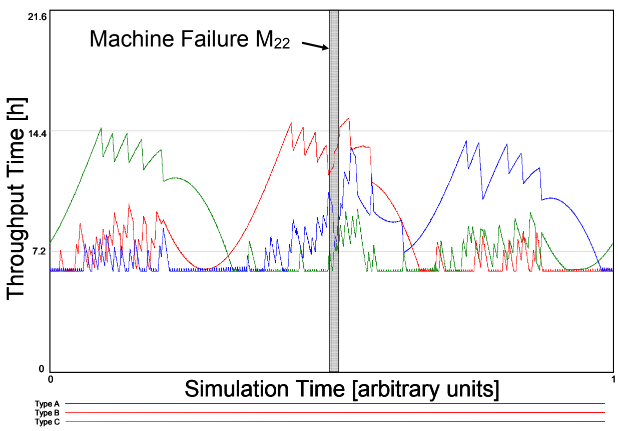

Figure 8: Throughput times in case of autonomous control and machine failure, continuous model.

This effect can be described as follows: Compared to the throughput times in the case of decisions based only on information about the lot size to be reached, the workload that exceeds 100 % can be passed on to another production line.

Finally, a failure of machine M_{22} and a downtime of 12 hours are considered. Figure 8 shows a sudden rise of the throughput times and again the distribution of the work between the lines. Compared to the results of the discrete-event model (Figure 5), the increase of throughput times is notably smaller because the system can react faster and redirects the workload almost instantaneously. Compared to the case without machine failure, the mean throughput time and the standard deviation respectively for lot type B increases slightly from 8:07 h to 8:10 h and from 2:14 h to 2:18 h respectively (see Table 3). This shows the model's ability to cope with unexpected machine failures.

5 SUMMARY

This paper presented two different approaches for modelling and analysing an autonomously controlled shop floor: A discrete-event simulation model and a continuous System Dynamics model. For the chosen arrival pattern it was shown that the autonomous control strategies can reduce throughput times and are robust against unexpected disturbances. But the models may react sensitive on different arrival pattern. Here, further research is in process.

Modelling by a discrete-event simulation tool allows a good description of real-world shop floor processes, but implementing autonomous control strategies requires high programming effort. In contrast, the continuous System Dynamics model allows an easy implementation of autonomous controls, but describes logistic processes on a higher aggregation level. To capture the mentioned interdependencies between local and global behaviour of autonomous controlled logistic systems, a dual use of both modelling approaches may be required.

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7 REFERENCES

[1] Kim, J.-H., Duffie, N. A., 2004, Backlog control for a closed loop PPC system. CIRP Annals 53/1:357-360.

[2] Scholz-Reiter, B., Windt, K., Freitag, M., 2004, Autonomous logistic processes. Proc. 37th CIRP-ISMS, pp. 357-362.

[3] Parunak, H. van Dyke, 1997, Go to the ant. Annals of Operations Research, 75, pp. 69-101.

[4] Ueda, K., Markus, A., Monostori, L., Kals, H.J.J., Arai, T., 2001, Emergent synthesis methodologies for manufacturing. CIRP Annals, 50/2:535-551.

[5] Peters, K., Worbs, J., Parlitz, U., Wiendahl, H.-P., 2004, Manufacturing systems with restricted buffer sizes. Nonlinear Dynamics of Production Systems, Wiley, Weinheim, pp. 39-54.

[6] Chase, C., Serrano, J., Ramadge, P., 1993, Periodicity and chaos from switched flow systems. IEEE Transactions on Automatic Control, pp. 70-83.

[7] Scholz-Reiter, B., Peters, K., de Beer, C., 2004, Autonomous Control of Shop Floor Logistics. Proc. IFAC-MIM, in print.