Autonomous control of a shop floor based on bee’s foraging behaviour

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This paper focuses on the application of a bee-like autonomous control method to a matrix-like shop floor model with setup times. Autonomous control means decentralized coordination of intelligent logistic objects in a dynamically changing environment. By the aid of a continuous flow simulation the system’s performance will be analyzed in regard to the application effect on throughput times and inventory levels.

1 Introduction

The ability to cope with increasing internal and external dynamics and complexity grows more and more to the crucial factor of company’s going concern. Shorter delivery times in connection with increased schedule performance in the field of multi-stage delivery chains are only few new market conditions present companies have to deal with. These changes require continuous improvement of production responsiveness and call for more flexibility of production and logistic systems.

Apparently present production planning and control systems are unable to cope with this kind of complex dynamics [1]. This leads to the introduction of autonomous control strategies. In accordance to the definition of autonomous control [2], this term can be understood as the decentralized coordination of intelligent logistic objects and their autonomous routing through a production system. For the application it is necessary to develop local decision rules that allow the autonomous decision making while the global objectives are reached through interaction and emergent behaviour [3, 4].

Different autonomous control strategies have been developed for different scenarios with varying processing times, with and without the consideration of setup-times. The queue length estimator [5, 6] is based on local information of buffer levels and the resulting expected waiting times. In addition a pheromone-like control approach was introduced, which uses data from past events and is inspired by ant’s foraging behaviour [7]. This paper aims on the introduction of a further biologically inspired, but non-pheromone-based strategy that utilizes the mechanisms of bee’s foraging behaviour and communication to design new rules to improve the ability of production systems to deal with increasing dynamics.

2 Autonomy in production logistics

The core of the concept of autonomous control is the development of decentralized and heterarchical control methods to react contemporary and efficient to changes in the complex and dynamical environment. The decision making process is transferred to the single logistic objects (e.g. machines, parts etc.) that control themselves autonomously by the application of recent information and communication technologies such as radio frequency identification (RFID), sensor networks or wireless communication networks. These technologies can be understood as enablers for intelligent products and parts to process information, to render decisions and to communicate with other logistic objects [8].

The goal of application of autonomous control strategies is the achievement of increased robustness and positive emergence of the total system by allocated accomplishment of dynamics and complexity of non-deterministic systems by higher flexibility and autonomy of decision making. To develop and analyze such autonomous control strategies Scholz-Reiter et al. [9] introduced a matrix-like shop floor scenario, which is modified to proof the capability of the bee-like approach to deal with problems like setup times and unexpected disturbances. The scenario is modelled with the System Dynamics methodology in a continuous flow model as this allows implementing feedback loops according to current data during the simulation easily.

3 Shop floor scenario

The considered shop floor consists of m parallel production lines with each n machine M_{ij}. Each machine has an input-buffer B_{ij} in front of it. K different products can be produced within this system (cf. Fig. 1).

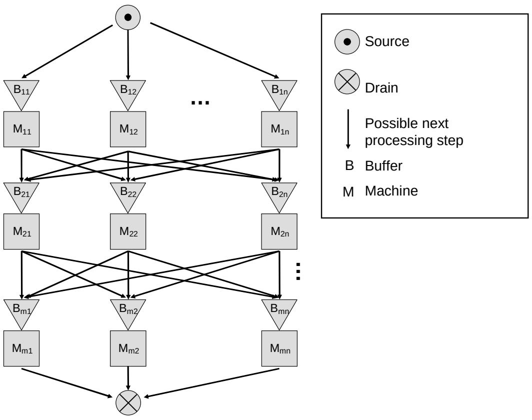

Fig. 1. Schematic illustration of the mxn shop floor scenario

At the source the raw materials for each product type enter the system. We assume that the different product lines are more suitable for certain products: in other words each machine at each stage has different processing times for each product; and each product type has a preferred line For simplicity the priority rule for the different products is set to first-come-first-served (FCFS).The production lines are coupled at every stage. That means every line is able to process every kind of product and the parts can switch to a different line at each production stage. They can decide autonomously to change their basic process plan and to use a parallel machine instead in times of overload.

4 Autonomous control based on bee’s foraging behaviour

Nature often acts as model for the development of new ways to deal with uncertainties in the production environment. Colonies of insects like ants and bees show an impressive behaviour, which has been classed as Swarm-Intelligence [10]. The individuals follow simple rules that allow solving complex problems beyond the capability of the single group members. These colonies are characterized by adaptiveness, robustness and self-organization [11]. It has been suggested that these adaptive properties can lend themselves to distributed optimization problems i.e. in the field of telecommunication, transportation and manufacturing.

Searching for new ideas for autonomous shop floor control the bee’s foraging behaviour can act as a proper model. There are several interesting control mechanisms based on simple rules that can be transferred to these specific problems.

4.1 Choosing the best feeding place in a honey bee colony

A colony of honey bees usually has different food sources to choose from. Bees that are aware of a food source can either advertise the source by performing a ‘waggle dance’, they can continue to forage at the food source without recruiting nest mates, or they can abandon and go back to a pool of unemployed bees [11]. If the bee decides to start dancing it conveys information about the known food source to the ‘onlooking’ bees, i.e. its general direction, distance, and quality [12]. It has been experimentally shown that if a colony is offered two identical food sources with the same distance from the hive, the bees exploit the sources equally. Nevertheless, if one source is better the bees are able to exploit or switch to it, even if it was discovered later. The probability of recruiting an onlooker bee for a particular flower patch is directly proportional to the number of dances performed for that source. The length of those dances in turn is proportional to source quality [13, 14]. Thus more bees will be recruited to better food sources usually.

Each homecoming collecting bee evaluates the food source by means of the ratio of energy consumption to the energy conveyed to the hive in form of sugar concentration. The better the individual evaluation of the food source quality is the more dance runs the bee will perform. Experiments have shown that onlooker bees watch only one single dance while meeting a dancing bee by chance. Usually the onlookers leave the dancing bee before it completes its waggle dance. Thus the more runs the dance has the longer it takes and the more unemployed bees can watch it. And, the more collecting bees are attracted the more dances are accomplished. A positive feedback loop emerges [15]. However, if the environment changes this food source can be displaced. Thus the decisions making is reversible [13, 14, 15].

4.2 Transfer of best feeding place choice to the best machining program problem

Searching for new approaches for production planning and control parallels occur between the decision making process of finding the best feeding place and finding the best way through a production line. In the same way the bees have to decide, which flower patch to travel to, in an autonomous production the part itself has to decide, which machine to go to in the next processing step.

One can imagine that even if a machine offers a very good processing time, the transportation time and waiting time should also be included into the decision making process. The throughput time varies dynamically over the time i.e. in consequence of different machining performance for different products, setup times and queue lengths.

The equation for the source quality can be found at Seeley [14, 16]. This ratio is the basis for the decision how many runs the next waggle dance will have. It expresses the ratio of the gain of a food source in Joule reduced by the costs and divided by the costs in Joule

$$\text{source quality} = \frac{\text{gain}\,[\text{J}] - \text{costs}\,[\text{J}]}{\text{costs}\,[\text{J}]}. \tag{4.1}$$

Transferring this mechanism to the machine scenario this means that a part leaving the machine after its processing has to decide about the duration of a signal given back to the following part. The signal strength is set to the value of 1 according to the one single bee performing a dance. According to the bee mechanism a part's choice of the next machine is depending on the sum of signals performed by the preceding parts (depending on the number of signals and the length of the signals). In the production scenario the evaluation equation expresses the ratio of the value added at one device reduced by the costs (caused by time spent for processing, transportation and waiting for each machine and product type) divided by these costs in monetary units [MU]

$$\text{machine quality} = \frac{\text{value added}\,[\text{MU}] - \text{costs}\,[\text{MU}]}{\text{costs}\,[\text{MU}]}. \tag{4.2}$$

For the application to the simulation model the machine quality $MQ_{mnk}(t)$ of each machine n on each production stage m and product type k is generated by the reduction of value added VA_{mk} to the part k on production stage m [MU] by the throughput time $TPT_{mnk}(t)$ of a certain product type in a machine n on stage m [TU] multiplied by the cost rate R in monetary units per time unit divided by these costs as a time dependent function:

$$MQ_{mnk}(t) = \frac{VA_{mk} - TPT_{mnk}(t) * R}{TPT_{mnk}(t) * R}. \tag{4.3}$$

5 Simulation Results

5.1 Scenario without setup times

The simulation model is reduced to 3x3 machines producing 3 different products in order to handle the complexity. To model a highly dynamic market situation the demand for the different products is set as an oscillating curve with situations of over and under load. Therefore the arrival functions is for all product types sinusoidal with an amplitude a_1= 0.25 and identical except for a phase shift of 1/3 period. Every 2:24 h a new part of every type arrives to the system. The processing times for the products are cyclic: 2 h, 2.5 h and 3 h respectively for the first, second and third best machine respectively. After a phase of another 30 days to avoid transient effects the second month is chosen to analyze the throughput time and input buffer level behaviour.

Fig. 2 shows the buffer levels of the three machines on the first production stage. The buffer levels of the first production step are only considered because the following stages act qualitatively in the same way but with an influx, which is smoothed by the processing times of the machines. The left side shows the system's behaviour in the case of conventional control. Conventional control means centralized pre-planned policy that schedules the parts to the line with the lowest processing time.

Because of the identical arrival functions (except for the phase shift) the time series of the buffer levels have the same shape. The buffer levels illustrate the oscillations of the given sinusoidal arrival functions. Within one simulation period we can observe the three maxima IB_{max} at 5.41 pieces and the mean buffer level IB_a of 3.07 pieces with a standard deviation IB_{std} of 1.02 pieces. One can observe that the curve shapes and key figures are identical for the autonomous control approach without a machine break down (top).

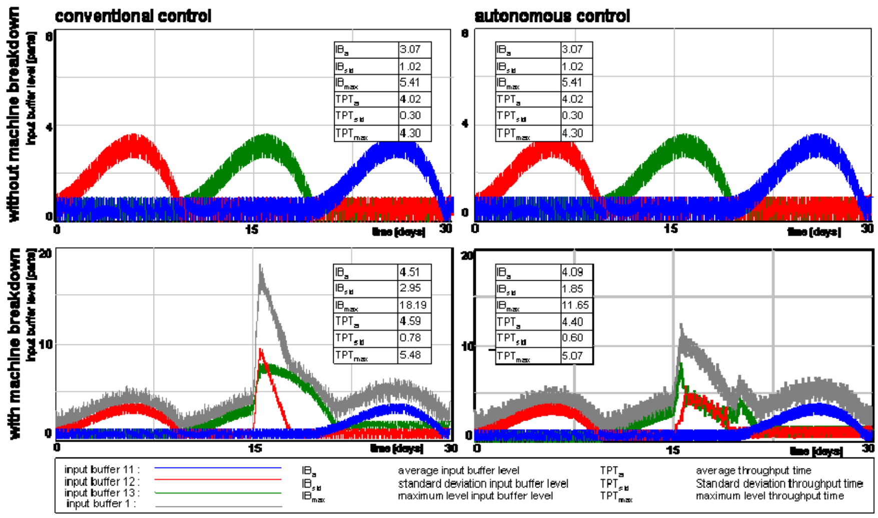

Fig. 2. Input buffer level behaviour comparison for a conventionally controlled and an autonomous controlled production scenario

To analyze the robustness of the bee concept a 12-hours machine breakdown was modelled. The comparison in the lower part of Fig. 2 shows that while the conventionally controlled system piles up the parts in the respective buffer until the machine starts to work again, the autonomous controlled system allocates the workload more efficient. The maximum buffer level is dramatically reduced from 18.19 pieces to 11.65 pieces. Thus the standard deviation of input buffer levels is decreased to nearly two thirds of the former value, from 2.95 pieces to 1.85 pieces and the mean buffer level is reduced from 4.51 pieces to 4.09 pieces.

The effects on the buffer levels are reflected by the throughput time behaviour. The mean throughput time TPT_a is increased compared to the systems without disturbances from 4.02 h to 4.59 h for the conventionally controlled system and only 4.40 h in the autonomous system. The maximum throughput time TPT_{max} reaches 5.48 hours for the conventionally control and 5.07 h for autonomous control compared to 4.30 h in case of no disturbance. However, the most interesting key figure may be the standard deviation of throughput time TPT_{std}. For the conventionally controlled system it is increased to 0.78 h compared to 0.30 h without a machine breakdown while the autonomous controlled system is only increased to 0.60 h.

5.2 Scenario with setup times

To design a more realistic scenario the meaning of setup times are added. For this purpose we assume that each machine n at each stage m has the same processing time of 2:00h for each product. A setup time is added if the product type changes (table 1). Thus, the machines’ priority rule for the choice of one part out of the buffer has to be adjusted to this new situation. As a simple approach a priority rule based on the queue length estimator is chosen [5, 6]. This rule leads to the complete depletion of a certain type of parts in the buffer before a change to another product type is accomplished.

Table 5.1. Setup times for product changes on the different machines

Setup times [min] product type x → y	**machine Mm1**	**machine Mm2**	**machine Mm3**
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

The core of the idea is the communication of the actual setup status to the parts entering the production system. These parts take the additional information into account for their decision making process, which buffer to go to.

Although there is nothing comparable in a beehive system to setup times in a machine system, it is possible to do justice to the meaning of setup times in the existing idea. In the previous section the signal strength was set to 1. By changing the signal strength to a higher value for the duration of only one time step a special advertisement can be given only to the direct successor part.

Table 5.2. Comparison of input buffer levels and throughput time key figures for different workloads and without and with transfer of setup status information

amplitude		**0.3**		**0.5**	
Setup status advertisement (yes/ no)		no	yes	no	yes
INPUT BUFFER	IB_a	5.88	5.74	6.89	6.44
	IB_{std}	1.78	1.02	1.76	1.50
	IB_{max}	11.87	9.07	13.38	11.45
THROUGH-PUT TIME	TPT_a	6.68	6.18	7.37	6.91
	TPT_{std}	0.46	0.20	0.38	0.25
	TPT_{max}	7.83	6.79	8.50	7.43

Table 2 shows that the enhanced control method improves all key figures for the input buffer levels and the throughput time. The simulation study has shown that the positive effects on the value are higher the more dynamical changes of the varying workloads are. Table 2 shows the results for a sinusoidal workload with an amplitude of a_2=0.3 and a_3=0.5: The standard deviation of throughput time TPT_{std} is decreased for more than the half amount for amplitude a_2 (from 0.46h to 0.20h) and for one third for amplitude a_3 (from 0.38h to 0.25h). In both cases the maximum buffer level IB_{max} can be reduced for approx. 2 pieces from 11.87 to 9.07 pieces and from 13.38 to 11.45 pieces. Moreover the mean buffer level IB_a is reduced from 5.88 to 5.74 for a_2 and from 6.89 to 6.44 pieces for a_3.

6 Conclusion

It was shown that a non-pheromone-based autonomous control strategy can be applied successfully to shop floor scenarios with set-up times. In comparison with a conventionally controlled line production the autonomous controlled system based on the bee's foraging behaviour shows promising results. The simulation proves that new control method can cope with unexpected disturbances like machine breakdowns much better than a conventionally controlled system. Key figures representing the production logistic objectives like throughput time and buffer levels are improved significantly. Furthermore the additional implementation of setup times pointed out the quality of the new control method, especially in dealing with situations of highly dynamical environment, is not only possible but even improves the results of the proposed idea.

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