Bio-inspired capacity control for production networks with autonomous work systems

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Abstract
To analyze behavior and performance of bio-inspired capacity control for production networks with autonomous work systems, a System Dynamics simulation model of a production network including real world data was developed. Two bio-inspired autonomous control strategies, namely an ant-like pheromone-based strategy and a strategy based on bee's foraging behavior, were implemented and simulations were run to find answers to the questions: How to design the (local) bio-analogous controller to achieve the desired global behavior? How do different bio-inspired control strategies perform in a capacity control scenario?

Keywords:
Capacity control, bio-inspired, production logistics

1 INTRODUCTION

Production networks are usually understood as geographically dispersed production facilities of one or few companies [1]. Capacity control policies for production networks deal with the coordination of resource use by adjusting capacity to achieve low throughput times and adherence to due dates. Unfortunately, production networks can exhibit unfavorable dynamic behavior and their structural complexity inhibits the collection and processing of the necessary information for a centralized planning and control [2].

In order to cope with the increasing dynamic and structural complexity of production networks, autonomous control strategies are of interest to study. In prior work it has been shown, that decentralized decision making by means of autonomous cooperating logistic processes is a capable approach for job-shop scheduling tasks [3]. Especially bio-inspired control strategies that copy the behavior of e.g. social insects can offer both, excellent logistic performance as well as an adaptive, robust against dynamical disturbances and self-organized behavior [4], [5], [6], [7]. Autonomous control strategies have been adapted to capacity control scenarios in prior work (cf. [8], [9], [10], [11]) in order to deal with unfavorable dynamics of external or internal order flows, internal disturbances like machine breakdowns and the local control laws itself. So far, there has not been an adaption of bio-analogous control for these scenarios.

This paper serves as a proof of concept that bio-inspired capacity control can be established. To achieve this goal, a System Dynamics simulation model of a multi work system production network with control of work system capacity using the Vensim DSS software is presented. Then, two different bio-inspired capacity control strategies, namely an ant-like pheromone-based strategy and a strategy based on bee's foraging behavior, are developed and implemented. Finally, the dynamic behavior of the bio-inspired capacity control strategies is illustrated using both, artificial input data and data from a forging company that supplies components to the automotive industry.

2 BIO-INSPIRED CONTROL IN PRODUCTION LOGISTICS

In literature one can find several attempts to explain the emergent behavior of large scale structures in biological systems. Camazine et al. [12] offer an overview and some case studies of self-organization in biological systems. The case studies comprise social insects, slime moulds, bacteria, bark beetles, fireflies and fish. According to the authors biological self-organization can be found in group-level behavior that arises in most cases from local individual actions that are influenced by the actions of neighbors or predecessors and in structures that are build conjointly by individuals. Colonies of social insects, e.g. ants or honey bees, show an impressive behavior, which has been classified as Swarm-Intelligence [13]. The individuals follow simple rules that allow solving complex problems beyond the capabilities of single group members. These colonies are characterized by adaptiveness, robustness and self-organization [12].

In view of the dynamics and complexity of production networks, the idea to employ bio-inspired control seems to be a promising approach: One may let nature act as an archetype for the development of new ways to deal with uncertainties in the production environment. Bio-inspired control in production logistics deals with finding parallels that occur between the decision making process in biological systems, i.e., in finding the best feeding place, and in production environments, i.e., in finding the best way through a production network.

2.1 Food foraging behavior of ants

In ant colonies for example, a scout ant that has found food lays down a pheromone trail as it returns to the nest, thus changing the environment. Succeeding ants may simply follow the trail and find the food and reinforce the trail with their pheromones or decide to search for a different food source.

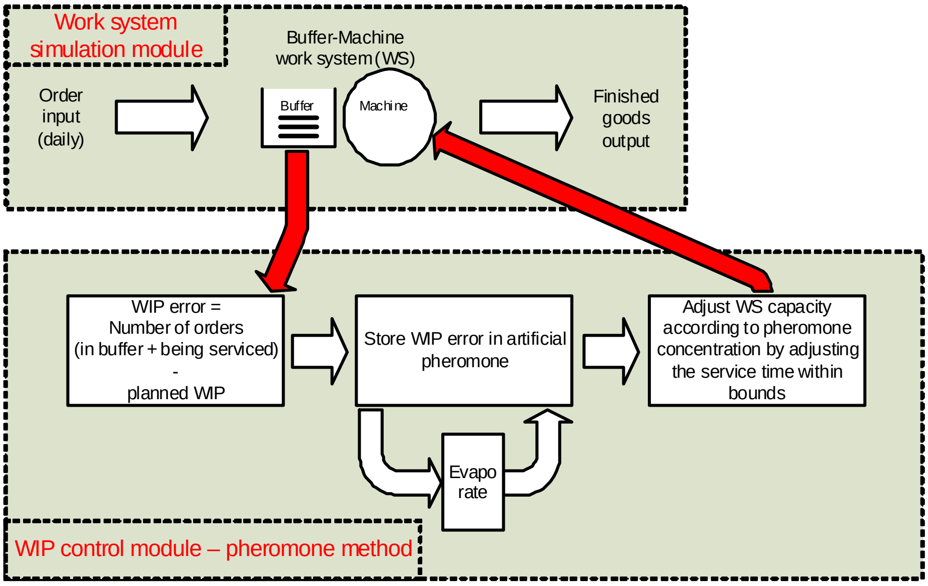

Figure 1: Interaction between pheromone-based WIP control module and work system simulation.

The pheromone evaporates over time guaranteeing that the strongest pheromone trails will be used and reinforced [13].

2.2 Food foraging behavior of honey bees

The food foraging behavior of honey bees is slightly different. Bees that are aware of a food source can advertise the source in order to recruit nest mates by performing a 'waggle dance'. With the help of the dance, the bee conveys information about the known food source to the 'onlooking' bees, i.e. its general direction, distance, and quality [14]. The probability of recruiting an onlooker bee for a particular flower patch is directly proportional to the number of dances performed for that source and the length of such a dance is proportional to source quality [15]. 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 [16].Thus, the more runs the dance has, the longer it takes and the more unemployed bees can watch it and are attracted to the best food sources.

Applications of the pheromone concept for scheduling tasks on the shop floor level can be found for example in [4], [5] or [17]. The honey bee concept has been adapted to flexible flow shop scheduling problems as well [6]. So far neither has been adapted to capacity control scenarios.

3 BIO-INSPIRED CAPACITY CONTROL DESIGN

Two bio-inspired capacity control methods were developed, i.e., the pheromone-based capacity control that mimics the food foraging behavior of ants and the honey bee capacity control method that mimics the food foraging behavior of honey bees were established to be tested within a computer simulation.

3.1 The pheromone capacity control method

The pheromone-based capacity control strategy is designed as follows: Every time an order arrives at the buffer of a work system it leaves information in form of an artificial pheromone, which is subtracted from the aggregated value each time the order is processed, i.e. leaves the machine. Thus, the aggregated pheromone concentration value represents the need for capacity to process the complete buffer contents. For simplicity, capacity is assumed to be adjusted on a daily basis. Then, the concentration of the artificial pheromone at the end of a shop calendar day represents simply the error in WIP at this machine.

The artificial pheromone is set to evaporate each day at a selected rate. The pheromone capacity control method reduces WIP error by adjusting the service time of the work system with respect to planned capacity and the current pheromone concentration. See Figure 1 for the two modules structure of the pheromone capacity control module within the computer simulation.

3.2 The honey bee capacity control method

The honey bee capacity control method uses the experience of parts as well. Whenever an order is processed it leaves two values: Equivalent to the ratio of energy consumption to the energy conveyed to the hive the honey bee calculates the WIP error by subtracting the planned WIP from the total number of orders. This value represents the need for capacity to process the complete buffer contents. In a second step, the order calculates the distance between the needed capacity and the planned WIP, which is the absolute value of WIP error, and decides on how long the corresponding adjustment should be in place: the higher the WIP error, the smaller the number of planned dance runs and vice versa. The order leaves his information as the number of dance runs as well. For simplicity, capacity is assumed to be adjusted on a daily basis. Then, the waggle dance duration value at the end of a shop calendar day represents simply the error in WIP at this machine and the number of dance runs value represents the number of days the capacity should be adjusted. The honey bee capacity control method reduces WIP error by adjusting the service time of the work system with respect to planned capacity and the calculated number of shop calendar days. See Figure 2 for the two modules structure of the honey bee capacity control method within the computer simulation. Both, the pheromone capacity control method and the honey bee capacity control method adjust capacity not only the next day but influence, with less impact and according to the evaporation rate or the calculated number of dance runs respectively, the capacity adjustments of the succeeding days as well.

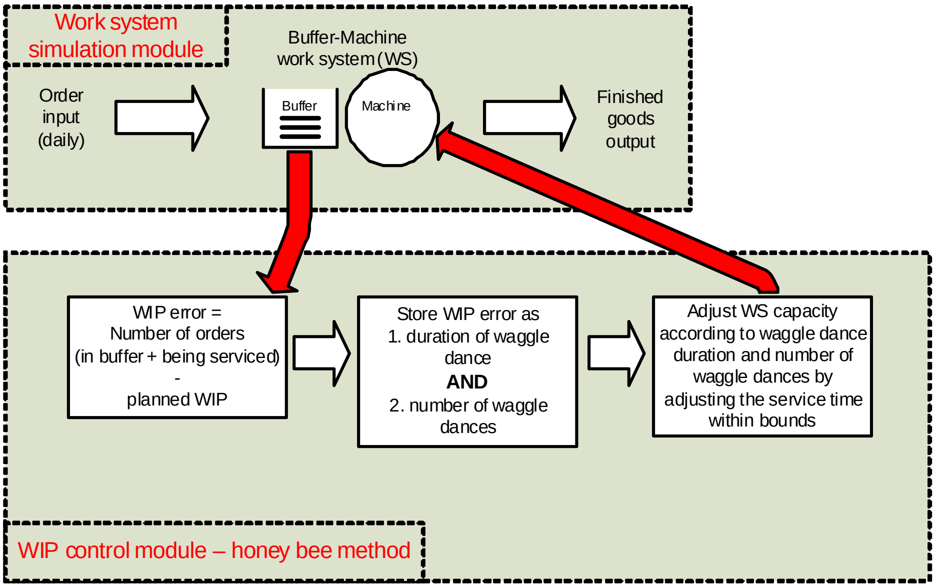

Figure 2: Interaction between honey bee inspired WIP control module and work system simulation.

Therefore, gain factors that keep the future impact into account are needed and because of the delayed partial adjustments the performance of these control methods will be inferior to control strategies without delays. Service time adjustments on the other hand are often in conflict with labor contracts and other operational issues.

4 COMPUTER SIMULATION

In order to assess the behavior of the pheromone capacity control method and the honey bee capacity control method they are tested with two different artificial scenarios, i.e. their ability to respond to a step input as an example for a rush order and to an alternating input as an example for a seasonal variation. After that, the result of the simulation with industrial data input is given.

4.1 System Dynamics Simulation Model

A multiple work system scenario was established. Its structure follows the production data from a forging company that supplies components to the automotive industry. The company's basic products are starter ring gears; other products include sensor wheels with machined teeth and flywheel assemblies for manual transmissions. The data documents 659 orders that entered the system from shop calendar day (scd) 162 to scd 347 in the year 2001. For purposes of analysis, the production system was grouped into five work systems listed in Table 1.

Work system	Planned capacity (orders/scd)			planned WIP (orders)	Duration (scd)
	Mon-Fri	Sat	Sun		
1. Shearing /Sawing	4.72	0.92	0.00	21.07	181-244
2. Ring rolling	5.34	1.50	0.00	18.92	181-244
3. Drop forging	2.95	0.42	0.00	14.46	181-244
4. Heat treatment	2.70	2.50	1.92	14.87	181-244
5. Quality control	6.28	0.83	0.08	72.11	188-265

Table 1: Planned capacity and WIP.

The planned capacities and WIP listed in Table 1 are averages obtained from the data; the time periods over which the plan was used in the model is also listed in Table 1. Table 2 illustrates the order flows between the work systems.

from \ to	0	1	2	3	4	5
0	0	341/659	295/659	1/659	7/659	15/659
1	0	0	106/341	235/341	0	0
2	9/401	0	0	0	188/401	204/401
3	7/236	0	0	0	100/236	129/236
4	27/295	0	0	0	0	268/295
5	616/616	0	0	0	0	0

Table 2: Order flow matrix of 5 work system scenario.

A System Dynamics computer simulation model using Vensim DSS software was constructed to illustrate the behavior of a multiple work system example. The structure of the System Dynamics model consists of two modules: a single work system input-process-output module and a WIP control module (cf. Figures 1 and 2).

The Shearing/Sawing work system was selected for further analysis to assess the behavior of different capacity control methods because it did not receive input from other work systems. Order flow was modeled according to input data to the Shearing/ Sawing work system and is illustrated in Figure 3.

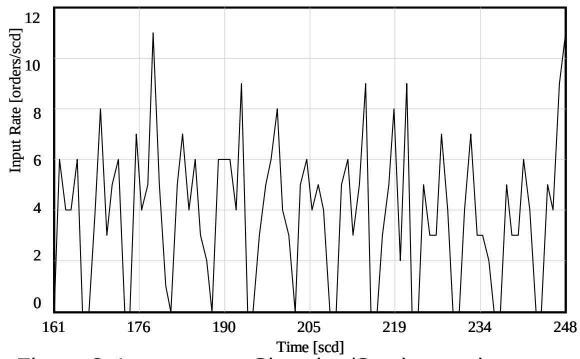

Figure 3: Input rate to Shearing/Sawing work system.

4.2 Response to step input (rush orders)

Pheromone capacity control method

Figure 4 shows continuous time System Dynamics simulation the response of WIP and the adjusted capacity to a single rush order at the Shearing/Sawing work system (100 orders released on scd 60 compared to the constant workload of 4.72 orders per scd) of the pheromone capacity control method.

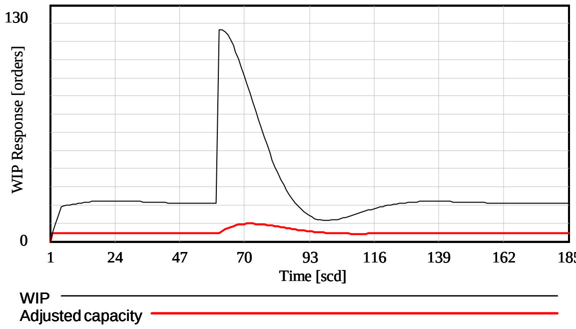

Figure 4: WIP response of the pheromone capacity control method to a step input.

Honey bee capacity control method

In Figure 5 the response of WIP and the adjusted capacity of the honey bee capacity control method (same parameters as above) can be seen.

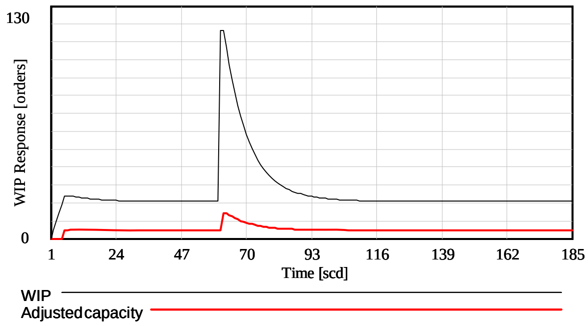

Figure 5: WIP response of the honey bee capacity control method to a step input.

Comparison

Comparing the simulation results illustrated in Figures 4 and 5, it can be seen that the pheromone capacity control method overshoots whereas the honey bee capacity control method does not. Time to normal is 97 for the pheromone method and 51 for the honey bee method.

4.3 Response to alternating input (seasonal variation)

In order to further analyze the behavior of the two bio-inspired capacity control methods, another artificial input was generated for the Shearing/Sawing work system. It alternates between 3.44 orders/scd to the average of 4.72 orders/scd to 6 orders/scd back to 4.72 orders/scd etc. in order mimic a seasonal variation.

Pheromone capacity control method

Figure 6 shows the simulation response of WIP together with the adjusted capacity to the described alternating input.

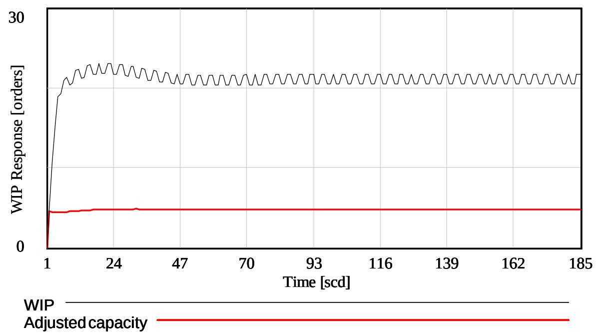

Figure 6: WIP response of the pheromone capacity control method to an alternating input.

Honey bee capacity control method

The response of WIP and the adjusted capacity of the honey bee capacity control method to the alternating input are shown in Figure 7.

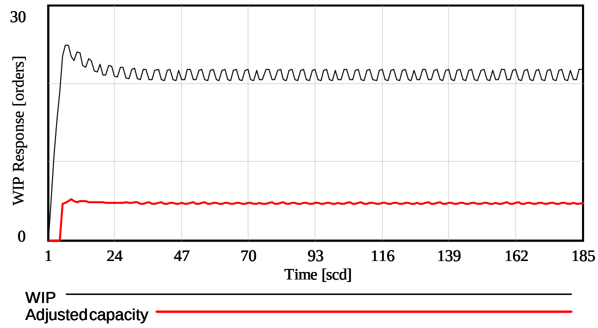

Figure 7: WIP response of the honey bee capacity control method to an alternating input.

Comparison

The simulation results depicted in Figures 6 and 7 show that the pheromone capacity control method overshoots again whereas the honey bee capacity control method reacts slowly at the beginning. The pheromone method keeps capacity constant whereas the honey bee method constantly applies very small changes to work system capacity.

4.4 Response to industrial data

Pheromone capacity control method

Figure 8 shows the response of WIP and the adjusted capacity of the pheromone capacity control method to the given industrial data (depicted in Figure 3).

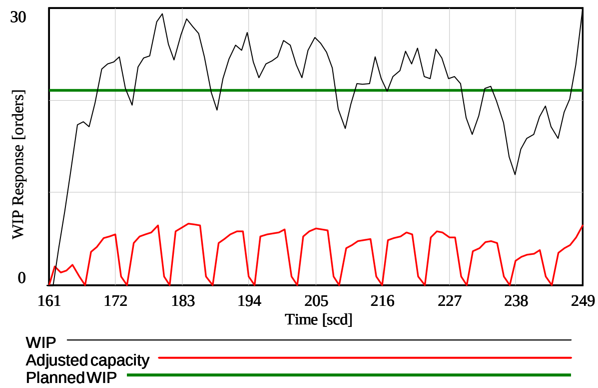

Figure 8: WIP response of the pheromone capacity control method to industrial data.

Honey bee capacity control method

The response of WIP together with the adjusted capacity of the honey bee capacity control method to the given real world data is illustrated in Figure 9.

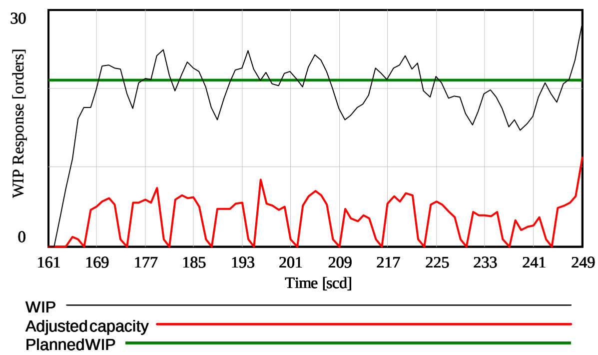

Figure 9: WIP response of the honey bee capacity control method to industrial data.

Comparison and evaluation

Comparing the simulation results of the two bio-inspired capacity control methods with industrial data input as depicted in Figures 8 and 9, it can be seen that both act qualitatively in the same way and the results can qualitatively be compared to a method relying on controller design in accordance with 'traditional' control theory (cf. [18]). The pheromone capacity control method's adjustments of work system capacity are more steadily compared to the capacity adjustments of the honey bee method, which adjusts more and faster. This results in smaller fluctuations of WIP and a lower average WIP of 19.93 orders/scd when using the honey bee method instead of the pheromone method, which has an average WIP of 21.88 orders/scd. The performance of the two new bio-inspired capacity control methods is higher that the documented WIP data from industry (cf. [18]).

5 SUMMARY

It was shown that bio-inspired capacity control methods can be established. A System Dynamics simulation model of a multi work system production network with control of work system capacity was presented. The pheromone capacity control method and the honey bee capacity control strategy were implemented. To assess the dynamic behavior of the two new control methods artificial input data in form of a step input and an alternating input was used. To proof the applicability of the new control methods, they were verified with real world data from a forging company. Comparing their performance in this context in terms of their ability to control WIP, it turned out to be in average lower and with less deviation from planned WIP than the documented WIP data from industry.

The two new control methods act qualitatively in the same way although the performance of the honey bee method is slightly higher at the cost of more and faster adjustments of work system capacity, which can be in conflict with labor contracts and other operational issues, if capacity adjustments have to be realized through service time adjustments as it was the case in the example.

To eliminate potential specifics of the industrial data, additional research is needed: The bio-inspired capacity control methods should be tested in a standardized scenario with multiple work systems, e.g. the mxn machine scenario presented in [3]. Furthermore, future research includes scenarios with limited overall capacities.

6 ACKNOWLEDGMENTS

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