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Inventory Control in Shop Floors, Production Networks and Supply Chains Using System Dynamics

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Abstract

The use of appropriate inventory control policies is a must in production systems. Production systems are characterised by structural and dynamic complexity. Material and information delays can occur, which may lead to inventory oscillations. In order to handle these dynamics, a system dynamics approach is used. It encompasses inventory control policies on the flow shop, the production network and supply chain level. For the shop floor level a pheromone-based decision policy is presented, which provides a flexible and autonomous control strategy. For the production network continuous and periodic inventory policies are combined. For the supply chain an adaptive order-up-to policy is developed by weighting the work in progress and the inventory. This paper presents an integrated view on inventory control in shop floors, production networks and supply chains in order to overcome the lack of flexibility that arises from long time delays of the strategic supply chain level by offering autonomous control on the operational shop floor level.

1 Inventory Control

It is important to keep inventory costs low; otherwise production will be less profitable. Inventory control is about the minimization of the average cost per time period while satisfying the incoming demand. Research on inventory control started at the beginning of last century boosted by the growth of manufacturers' activities. For the shop floor a pheromone-based autonomous control policy is proposed in section 2.1. Autonomous control means a decentralized routing of the autonomous parts themselves. Therefore there are no standard inventory policies here to apply. Thus, policies that enact the parts to decide autonomously, instantaneously and with local and present information only, which alternative to choose, are developed. Since costs of raw materials and finished goods stocks are not considered on the shop floor level, the only inventory costs arise from the buffer levels in this case. In a production network manufacturers integrate and coordinate the general net production plan according to their individual production planning to satisfy customer demand. Former studies proposed the application of order release control methods and decentralized control loops [Wie02]. In section 2.2 continuous and periodic control methods are applied to a model of a production network in order to find a policy that reduces inventory costs. Inventory costs for the production net are occasioned by products on hold and backlogs of items ordered and not yet available. The production planning and inventory control (PIC) on the supply chain level

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is challenged by highly complex products, dynamic production changes and uncertain market demand. The PIC has to optimise the inventory under the trade-off between capacity variation, buffer inventory and lead time. In order to optimise buffer inventory and lead time the order-up-to policy (OUT) is quite sufficient because it reacts fast to changes in demand. However, this policy generates high fluctuations in the production. In section 2.3 a decision rule addresses this problem by accounting for the adjustment time of the stocks as well as the fluctuating inventory and fluctuating production costs.

2 Inventory Control with System Dynamics

The system dynamics models of a shop floor, production network and supply chain will be presented. The three partial models are built and simulated with the continuous system dynamics methodology, which demonstrates the ability to describe the corresponding environments as long as the emphasis is not on the individual products and aggregation is allowed. Furthermore, the continuous perspective yields negligible errors in variables´ values. The method enables the modelling of dynamic and uncertain systems due to its inclusion of feedbacks, nonlinearities and shifting loop dominance.

2.1 Shop Floor

For the inventory control on the shop floor level a pheromone-based autonomous control policy is proposed. Autonomous control means a decentralized routing of the autonomous parts themselves. Therefore there are no standard inventory policies to apply. Rather policies enact the parts to decide autonomously, instantaneously and with local and present information only, which alternative to choose. First intuitive approaches are to set up a policy like 'go to the buffer of the machine with the shortest processing time' (we call it conventional control) or 'go to the machine with the lowest buffer level' [Sch05a] etc. Here, a different policy is presented: 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. In a simulation, the performance of the pheromone concept will be compared to a conventionally controlled system with respect to inventory.

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; 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 a decision to which of the lines to go to in the next stage. The service rule for the different products is first in - first out. Each machine has an input buffer in front of it, containing items of the three product types. Additionally, different product lines are more suitable for certain products: it is assumed that each machine at each stage has different processing times for each product (for the topology cf. also [Sch05a, Sch05b]). In other words: A part is

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punished when it decides to switch production lines. This punish-time can be interpreted as a setup time for each product that chooses to switch the production line. A scenario like this can be found in the food processing industry, where for example an enwrapping machine can enwrap different products in different times without any setups. This is different from scenarios where setup times are understood as a punishment only for the first part of the new type that switches production lines.

A pheromone-based inventory policy is implemented analogue to the way social insects communicate with the help of pheromones. As in other pheromone concepts [Bon99, Pee99], the communication takes place indirectly by changing the environment. Social insects leave an evaporating substance called pheromone on their way and the following insects proceed along the trail with the strongest pheromone concentration. In this model the parts have to be able to access updated information about throughput time only. Thus, the pheromone-based policy differs from approaches from ant colony optimization (for example [Bon99]) since there is no self-reinforcing guided search process for optimal solutions. The pheromone concentration depends on the evaporation of the pheromone and on the time previous parts had to spend waiting in the buffer in addition to the processing time on the respective machine as well as the throughput time. This scenario is simulated with the system dynamics method because it offers the opportunity to store not only the moving average of the throughput times for each part on each buffer-machine system [Arm06], but also to implement a feedback loop for the pheromone concentration according to actual data during the simulation. Clearly the fine-tuning of the evaporation constant for the pheromone is crucial. Here it was chosen in order to minimize the buffer levels. Previously proposed concepts for manufacturing control (e.g. [Pee99]) include a reinforcement of the pheromone trail when ants walk back their way to the nest. Here the parts simply disappear after the completion of the production steps.

In order to handle the complexity the simulation model is reduced to 3x3 machines producing 3 different products. The arrival functions for the three product types are defined as sine functions. They are identical except for a phase shift of 1/3 period and modelled in a way that every 2:24 h a new part of every type arrives to the system. The processing times for each product are cyclic: 2 h, 2.5 h and 3 h respectively for the first, second and third best choice respectively. For simplicity the buffer levels of the first production step are considered only because the following stages act qualitatively in the same way but with an influx, which is smoothed by the processing times of the machines. Figure 1A shows the buffer levels of the three machines on the first production step in the case of conventional control. Conventional control means the 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 (30 days) we can observe the three maxima at 8.73 pieces and the mean buffer level of 3 pieces with a standard deviation of 5.36 pieces. Figure 1B shows the buffer levels for the pheromone-based approach which performs very well. Obviously, this effect occurs because the parts learn to switch to other production lines in case of capacity overload even if the processing time is higher there. The maximum buffer level is reduced to 8.26 pieces and the mean buffer level is 3

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pieces with a standard deviation of only 3.05 pieces. To analyze the robustness of the pheromone concept, a machine failure for the second machine of the first stage is modelled with a 12-hours downtime. In the conventionally controlled system the parts pile up in the respective buffer until the machine starts to work again.

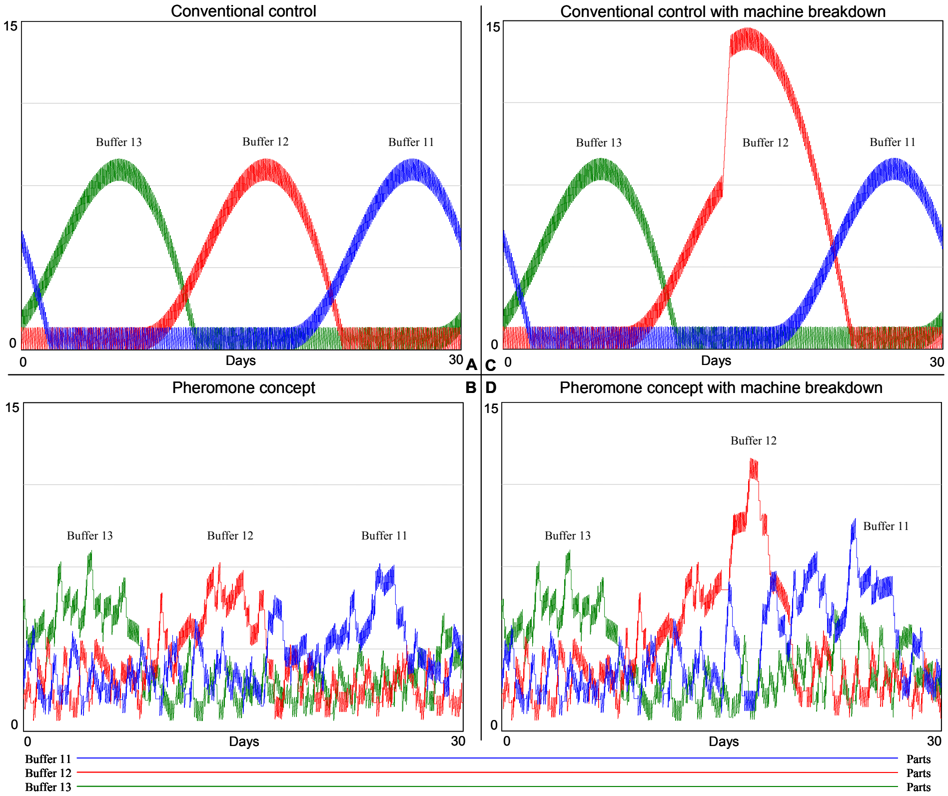

Figure 1: Buffer levels for the different inventory policies

The maximum buffer level for this machine rises to 14.67 pieces while the other lines remain unaffected (Figure 1C). The standard deviation rises to 5.62 pieces. Figure 1D shows the buffer levels for the pheromone-based policy in the machine failure scenario. The maximum buffer level is 13.44 pieces and the parts are distributed between the lines. In this case the standard deviation is 3.08 pieces. Again the pheromone-based inventory policy performs excellently. Additionally, it enables the shop floor to adapt itself to changing work loads and unexpected disturbances. Thus, in the presence of high dynamics, the pheromone concept can lead to lower inventory levels on shop floors. These results can be transferred to every other flow line manufacturing system as long as parallel production lines with different processing times for each different product (instead of setup times) are taken into account.

2.2 Production Network

Continuous and periodic inventory control rules are applied to a system dynamics model of the production network in order to find a policy that reduces inventory costs. The term ‘continuous policies’ describes an uninterrupted supervision of the inventory performed by the policies of (a) order point – order quantity (s, Q) and (b) order point – order-up-to level (s, S). On the other hand periodic review policies take constant order intervals into account. Here, we investigate (a) review period – order quantity (r, Q), (b) review period – order-up-to level (r, S), (c) review period – order point – order-up-to level (r, s, S), and (d) order inventory rule. In (d) the order is a function of the constant reacquisition time (time between the order is placed and the supply is made), the safety factor, the average demand as well as its standard deviation during reacquisition. The considered scenario (Figure 2) describes a production network with four manufacturers, Mi, i = 1..4, who jointly develop products. The manufacturer has four parallel production lines Lij, j = 1..4 and each of them produces one dedicated item Pij. The product Pij denotes product j manufactured by Mi. Each line is externally coupled with one of the other manufacturers´ production systems. There is also internal coupling within the same manufacturing unit. A production line has a work-in-progress (WIP) that stores the products before production and a stock of manufactured lots. The supply of raw materials for the WIP is assumed to be unlimited in capacity and it is done by an external supplier to the production line Lii (i = 1..4). This line receives customer orders and passes them to lines Lij. They are then delivered to the customer. The line Lij (i ≠ j) receives the quantity ordered to produce Pij from Lii. The semi-finished parts Pij, i, j = 1..4 (j ≠ i), are jointly developed by two manufacturers. The minimum lead time on Lij is denoted Tij. It includes the cycle time and the transport time from Lij (Mi) to Lji (Mj). Tij is constant.

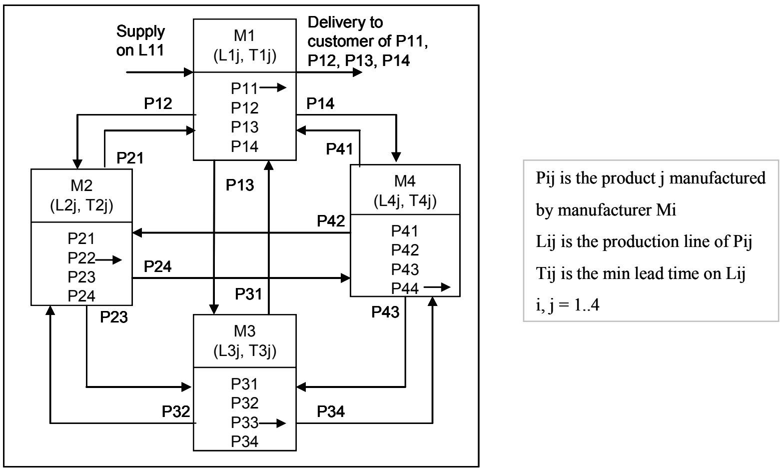

Figure 2: Production network structure

Although the model is a simplified theoretical instance of a production net, similar structures of re-entrant nets exist in real-life industries like semiconductors. The choice is on four manufacturers because that renders the behaviour of the net more challenging in terms of the feedbacks and nonlinearities created by the production and logistic processes.

The system dynamics model proposes a continuous modelling approach of the production system. Despite the different existing products, the focus is not on the individual item type - which is regarded as an aggregate lot. Rather the attention is on the dynamics created by the application of the different inventory control rules on the inventory oscillations measured by the cost function. Ordering costs are not considered. Instead a holding cost of € 0.5 for a product in inventory per minute is accounted for in addition to an out-of-stock penalty of € 1.0 per item in backlog per minute. The latter is charged double the former as a penalty for the risk of customer loss. The simulation period lasts two thousand minutes with a simulation step of one minute.

A step function was used to test the response of the model to a one hundred percent increase in customer demand for the products manufactured in the network at time one thousand minutes. Customer demand is therefore quasi-constant. Even though, ample oscillations appear in supply chains because of material and information delays, feedback structures and nonlinearities [Ste00]. The effect of the step function can be seen in the graph of the network’s average cost per minute. In this graph the best inventory policy can be hardly seen. Thus, the cumulative costs graph was chosen (Figure 3).

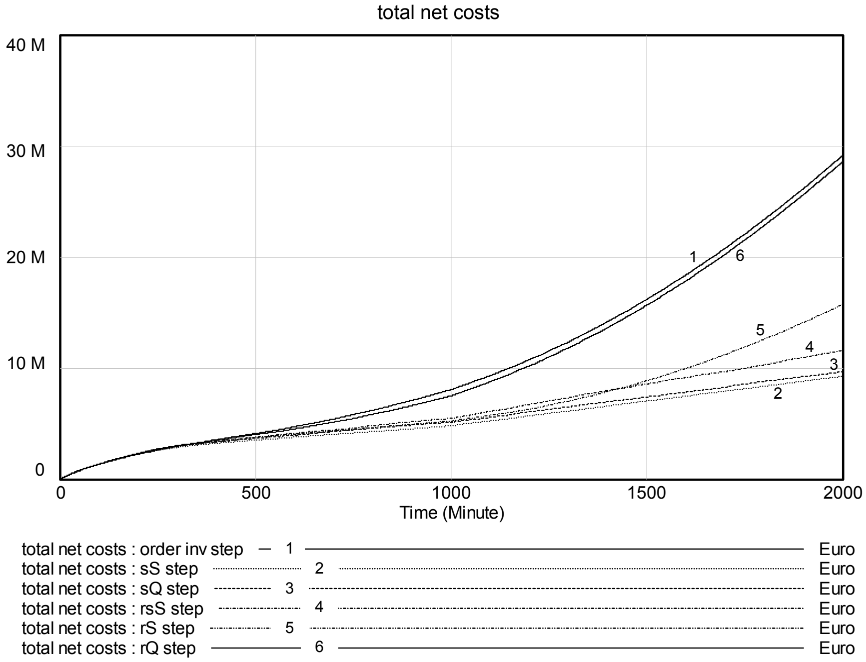

Figure 3: Cumulative costs of the production net based on average costs per minute

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After the iterative adjustment of the parameters of the inventory control rules (review period r, order point s, order up to level S, etc.) the models were simulated and the cumulative costs paralleled. The best inventory control policy for the production net is the order point – order-up-to level (s, S) rule. It has the capacity to adjust itself in case of uncertainty because both the order quantity and order interval change. At the opposite the review period – order quantity (r, Q) rule has the second highest costs because the constant order interval and order quantity cause this rule to be inflexible. Therefore, there is few practical evidence. The review period – order point – order-up-to level (r, s, S) policy provides twenty five percent costs more than the best (s, S) rule at the end of the simulation period because of the constraint on the fixed order interval r. Indeed when r is zero the (r, s, S) strategy turns to the continuous inventory supervision (s, S) rule. As expected the review period – order-up-to level (r, S) rule is more expansive than the (s, Q) policy.

2.3 Supply Chain

Production and inventory control in supply chains has to optimise the inventory under the trade-off between capacity variation, buffer inventory and lead time. In order to optimise buffer inventory and lead time the order-up-to policy (OUT) is quite sufficient. Furthermore, the OUT has the ability to react fast on changes in demand, but the policy generates high fluctuations in the production. These fluctuations often lead to reoccurring ramp-ups and shut downs of the production. Thereby production costs increase and the bullwhip effect amplifies. By adding smoothing parameters to the OUT policy a new classification of policies is generated: the inventory and order based production control system (IOBPCS) [Dej03]. If we set high smoothing parameters, the new smooth policy will generate less fluctuation in production. Unfortunately the minimisation of production oscillations is counterbalanced by a slower adaptation of the production to changing market demand [Dej03] and by higher buffer inventory levels in order to keep lead times at a constant level. A solution to this problem is determined: First, a supply chain is structured with the help of the system dynamics method. For this purpose a supply chain model from Sterman [Ste00] is adjusted. It contains the stock and flow structure and the IOBPCS decision rule. A new decision rule is implemented, which portrays the relationships between the adjustment time of the inventory and WIP, inventory coverage as well as fluctuating inventory and fluctuating production costs. Finally, both results are compared with respect to the ratio of output variance to input variance.

We investigate a fictitious global automotive supply chain, which consists of two supply chain elements: the production of parts and the assembly of a car. Both elements of the supply chain include the material supply line, the production line, the backlog of orders and the decision rules. Each supply chain element (company) has to make the decision about production start rate and material order rate. The exogenous input of the model consists of customer orders. In the following, one element of the supply chain, the assembly chain, is presented (Figure 4). The assembly chain has to fulfil customer demand. For this purpose the shipment rate from the finished parts inventory (FPI) has to be processed. The quantity of shipment is limited by the desired shipment and the available shipment rate. The stock of finished parts inventory (FPI) increases with the complete assembly rate and it decreases with the real shipment rate. The assembly rate is defined as a pipeline delay from the assembly start rate (A_s) with the time delay τ_a. Between the assembly start rate and the assembly rate the stock assembly work-in-progress (AWIP) is placed. The assembly start rate is defined as the sum of expected orders (EO), the difference between the target finished parts inventory (FPI*) and the actual finished parts inventory divided by the adjustment time (τ_{FPI}) and the difference between the target assembly work-in-progress (AWIP*) and the actual assembly work-in-progress divided by the adjustment time (τ_{AWIP}). The assembly start rate cannot be negative, so the maximum of zero and the described term is chosen as the assembly start rate.

$$A_s(t) = Max(0, EO(t) + \frac{FPI*(t) - FPI(t)}{\tau_{FPI}} + \frac{AWIP*(t) - AWIP(t)}{\tau_{AWIP}}) \qquad (1)$$

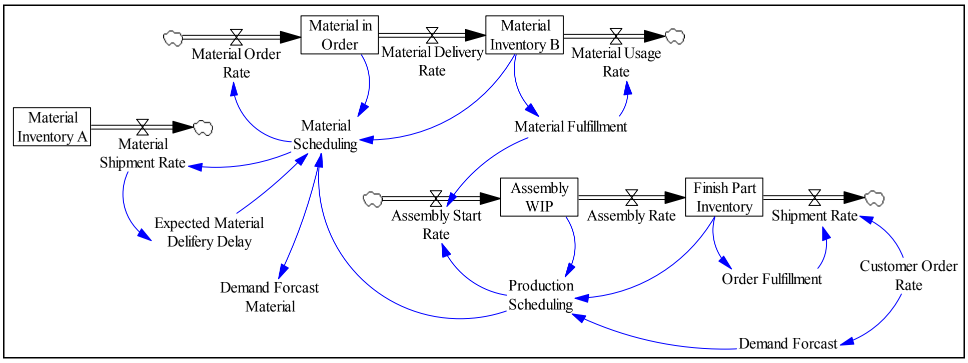


Figure 4: Overview of assembly and the control of assembly

Equation 1 describes the IOBPC policy for the assembly process. The same control policy is applied to the material supply of the assembly chain with one additional variable: the expected material delivery delay. This means the target material in order (MIO*), which is given by the target material delivery rate (MD*) and the expected material delivery delay (EMDD), cannot be determined with certainty. This is because of the uncertainty about the material delivery delay.

$$\mathrm{MIO}*(\mathrm{t}) = \mathrm{MD}* \cdot (\mathrm{t}) \quad \mathrm{EMDD} \qquad (2)$$

After we have described the basic stocks and flows as well as the basic decision rules of the two supply chain elements, we will cluster the adjustment times following Sterman´s argumentation [Ste00]. For this purpose we introduce the weight on the supply line (WSL), which is given by the ratio of the stock adjustment time (in our case τ_{FPI}) and the supply line adjustment time (in our case τ_{AWIP}). Using this ratio we can express the IOBPC policy in a different way. Therefore, we introduce the effective total stock (ETS). It consists of the FPI plus the product of WSL and the AWIP.

$$\mathrm{WSL} = \tau_{FGI} / \tau_{AWIP} \qquad (3)$$

$$ETS = FPI + WSL \cdot AWIP \qquad (4)$$

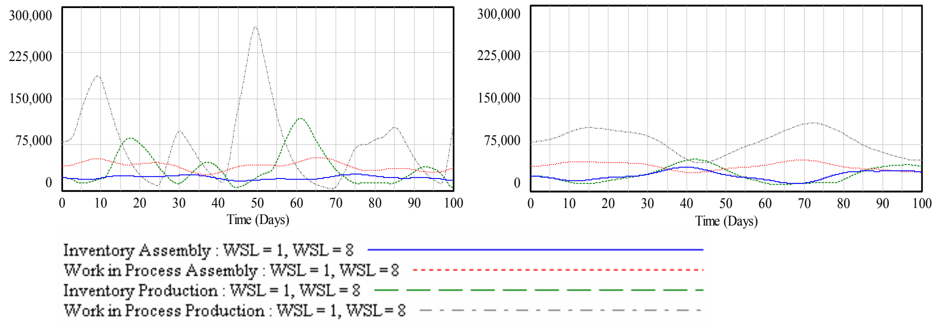
$$A_s(t) = Max(0, EO(t) + (ETS* - ETS) / \tau_{FGI} \qquad (5)$$

We adapt the IOBPC policy to the influence factor ‘cost ratio’ (CR), which consists of the ratio of the costs for production fluctuations (CPF) and the costs for inventory fluctuations (CIF). The CR is positively correlated to the WSL: The higher the relative inventory costs are, the smaller the WSL is, and the less inventory oscillations occur. The higher the WSL, the more inventory coverage is required to catch inventory oscillations. So, a factor relationship between WSL and inventory coverage (IC) is introduced.

$$CR = CPF \,/\, CBI \rightarrow WSL = \tau_{FPI} \,/\, \tau_{AWIP} \tag{6}$$

$$\mathrm{WSL} = \mathrm{a} \cdot \mathrm{IC} \tag{7}$$

We explore the trade-off between the production oscillations, inventory oscillations and the lead time in the presented supply chain model under the use of the adapted IOBPC policy. The model input is the order rate, which is determined by three sine functions with short, medium and large period times. The order rate has a mean of 10,000 orders and a norm standard deviation of 0.1420. The aim of the policies is to generate small inventory oscillations measured by the norm variance of the assembly and production inventory as well as small production oscillations measured by the norm variance of the assembly and production work-in-progress. For this purpose two settings of this new policy are used: Case 1: WSL = 1 and Case 2: WSL = 8 (Figure 5).



	OR	FPI	AWIP	IM	MIO	PI	PWIP
Case 1	0.1420	0.1385	0.1814	0.3802	0.9938	0.7734	0.7996
Case 2	0.1420	0.2870	0.1492	0.1308	0.3399	0.4810	0.2406

Figure 5: Norm standard deviation and graph for case 1 and case 2

In both cases the lead time is stable because the adaptive IOBPC policy considers inventory coverage. In addition the high uncertainty between the supply chain elements are proportional (cp. Figure 5 the variation of material inventory (IM) and material in order (MIO)). Especially in case 1, the ratio of the variance of inventory to the variance of work-in-progress is almost 1 since WSL = 1. These settings reduce the variance of the finished parts inventory but increase the bullwhip effect. In the second case the inventories oscillate more but the variance in the work-in-progress is extremely reduced. The second case is an example of how production oscillations and the bullwhip effect can be avoided by giving more weight to the supply line and letting the inventory oscillate more. The first case is adjusted for high inventory costs and flexible production.

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3 Discussion and Conclusion

Three partial models for a shop floor, a production network and a supply chain respectively were designed and different inventory control policies were applied. The aim of the paper was to find near optimal inventory control policies. For this, the performance as well as the dynamic behaviour on all three levels of the complete system was analysed. With the help of the system dynamics methodology, we were enabled to model the dynamics and uncertainty due to its inclusion of value-continuity, feedbacks, nonlinearities and shifting loop dominance. Through the testing, recombination and enhancement of existing inventory control policies as well as through the design and implementation of new ones, we have found near optimal inventory control policies for all three levels. The threefold model was needed in order to cover the interdependencies between the strategic and the operational level. On the level of the strategic planning of the material flow there are mutual contradictory aims between flexibility and stability. Influence factors for uncertain supply chains have been pointed out. With these factors it is possible to set the amount of flexibility while keeping the supply chain stable. To counterpart this we have demonstrated that it is possible to balance out the inventory and thus to regain flexibility on the operational level with the help of the pheromone-based concept. In the production net - even though an inventory control rule was found to reduce inventory costs - orders still remain a tactical task of schedulers.

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