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Design of a simulation model for the assessment of a real-time capable disturbance management in manufacturing supply chains

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Abstract

The steady increasing of supply chain complexity due to a rising global cross-linking of production and sales regions leads to an increasing sensitivity to disturbances while in the meantime the requirements of the availability, the time of delivery and the security of supplies within the supply chain increases. To meet this challenges the security of the supply chain infrastructure and the feasibility of supply chain processes need to be ensured, despite of the high specialization within the supply chain partners, the low stock and time buffers, and the information shortcoming between supply chain partners. In this research, a System Dynamics simulation model, based on the manufacturing supply chain model of Sterman, has been developed for representing the actual complexity and dynamic in manufacturing supply chains. Therefore, the modeled manufacturing supply chain shows the processes of a four level supply chain focusing the processes and interactions of the mid-positioned two supply chain participants. The main contribution of the work described in this paper, is the description and implementation of necessary additional modules and parameters to Sterman's basic model for the diagnosis of disturbance impacts as well as for the realization of supply chain adjustments. Finally, the model has been simulated and examined for realistic values.

Keywords: Supply chain; Simulation; Disturbance management; System dynamics

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1. Introduction

Due to a rising cross-linking of production and sales regions, the complexity of supply chains has steadily been increased. Consequently, an increasing sensitivity to disturbances can be observed, while in the meantime the requirements of availability, the time of delivery and the security of supplies within the supply chain increases. Through dynamic global markets, today, industrial companies are exposed to a high vulnerability. Secured supply chain infrastructures and feasible supply chain processes need to be ensured to meet these challenges, in spite of a high specialization with supply chain partners as well as low stocks, time buffers and information short coming between the supply chain partners [1,2,3]. To counteract these shortcomings, the High Resolution Supply Chain Management approach follows the idea of decentralized, self-optimizing control loops in the supply chain planning and a control system, based on a higher information transparency [4]. Therefore, ICT-based approaches such as the supply chain event management are developed to reduce the vulnerability of supply chains by providing real-time information of disturbances. But neither the correlation between disturbances and supply chain planning strategies for their moderation nor their effects on the supply chain costs and performance are sufficiently illuminated [5].

In the following research, a System Dynamics simulation model, based on the manufacturing supply chain model of Sterman, has been developed for representing the actual complexity and dynamic in manufacturing where the processes of a four level manufacturing supply chain are realized. The main contribution is the description and implementation of necessary additional modules and parameters to Sterman's basic model for the diagnosis of disturbance impacts as well as for the realization of supply chain adjustments. Furthermore, the system is modified to include an exposure to variable disturbances and a system for the measurement of supply chain costs and performances. Finally, the model has been tested for realistic values.

Before the developed model is going to be discussed, a short outline to necessary basics is given. Chapter two gives an overview on company processes and chapter three points out the System Dynamics approach and the main contribution of Sterman's supply chain model. Finally, the developed model is will be discussed with the added modules and parameters (chapter 4) and a short conclusion and an outlook will be given (chapter 5).

2. Definition of processes in manufacturing supply chains

In manufacturing companies three stages of production planning processes can be highlighted: The master production scheduling, production factors planning and production processes planning. The cross-sectional tasks of the inventory management support these three processes [6, 7].
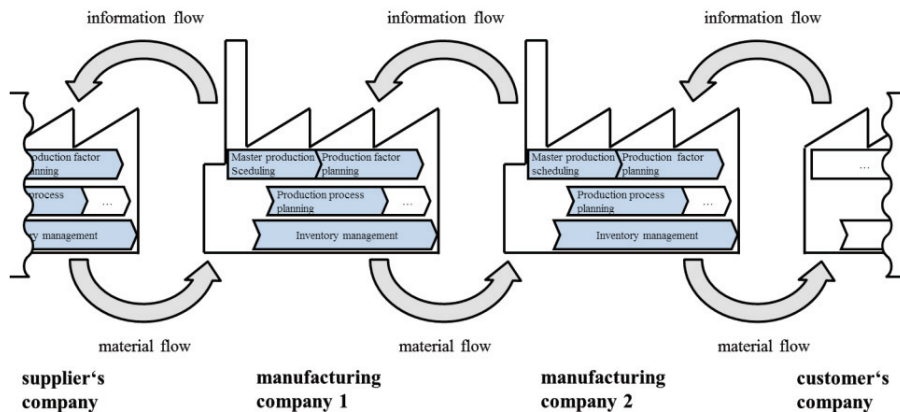

Fig. 1. Manufacturing supply chain and planning processes [8].

The master production scheduling determines which products and quantities are going to be produced in the following planning period and how these products and their quantities have to be distributed to the individual periods. The master production scheduling is splitted in the sub-processes sales planning, gross requirement planning, net demand assessment and resource rough planning. As a result, a coordinated production schedule has been created considering available production capacities and the company's expected sales. The produced quantity is called primary demand. In the manufacturing company, the primary demand is determined by consumption forecasts. On the contrary, the primary demand of suppliers is determined by blanket orders with the manufacturing company.

Based on the production schedule, production factor planning calculates the required production factors, i.e., equipment, workforce and materials, for producing the determined primary demand. The aim is to give detailed demands with regard to quantity and delivery date, which is defined as the secondary demand. The gross secondary demand does not consider the available stock inventory, so that the net secondary demand is calculated by the difference between gross secondary demand and available stock inventory.

Also based on the production schedule, the production process planning details the planning of production resources, quantities and dates. Its aim is to ensure that the determined primary demand is manufactured at the right time, in the right quantity and in the desired quality. The production process planning includes an order-orientated scheduling and a machine-orientated capacity requirement planning to determine the optimal machine order for manufacturing, material supply and staff planning.

Finally, the inventory management considers uncertainties, random influence factors, i.e., shortfalls in quantities, production disruptions or short-term rush orders. Tasks are the inventory planning, management and analysis as well as warehouse management.

3. Methodological approach and preconditions

John D. Sterman developed a continuous supply chain model by using the System Dynamics approach that has been developed by Jay W. Forrester at the Massachusetts Institute of Technology [8]. System dynamics provides a method to enhance the understanding of complex systems and their behavior by analyzing and simulating the observed system [8, 9]. The origin of that methodology is the cybernetics. Based on methods of the control theory, decision theory and different simulation technologies, System Dynamics deals with the interactions between different components of a system. An essential part of System Dynamics is the focus on analyzing feedback structures by using casual loop diagrams that enables a more holistic view of the observed system. System Dynamics models have been used to describe a wide range of problems in various fields, e.g., climate change, population growth, water resources and industrial systems [8, 11].

The model of Sterman can be divided in the inventory and production structure within the company, the material supply line for interactions with the suppliers and an order backlog structure for incoming order information. The basic structure of the model consists of the work in process inventory stock and the inventory stock with the finished products as well as the flows production start rate to initiate the manufacturing process, the production rate that indicates the finished products per period and the shipment rate for the dispatched products to the customer. Thereby, a high inventory and a low shipment rate mean high inventory coverage. Normally, the shipment rate is equivalent to the customer order rate, but if inventory is inadequate, shipment rate will be adapt to the inventory [8].

Sterman's model also maintains a backlog of unfilled orders where the difference between orders and shipments are accumulated, which means a delayed delivery. In the model every order in every period is assumed as an unfilled order. Depending on the available inventory all orders can be fulfilled or not, so that the shipment rate is simplified the minimum of inventory and backlog and is equivalent to the order fulfillment rate as the out coming flow of the backlog. In this part of the model the interface to the customer is also included as the order rate is equivalent to the customer order rate [8].

The production is represented by the work in process (WIP) inventory for the current produced products, where all stages of processes are aggregated together, and the out coming flow as the production rate depending on the production start rate and manufacturing cycle time. The productions start rate depends on a desired production start rate, that is determined by the WIP inventory, the inventory of finished goods, the desired inventory coverage and

the expected order rate. The expected order rate is the forecasted demand that is determined by the customer order rate and is calculated by Sterman using the technique of exponential smoothing [8].

The production start rate depends also on the material delivery. If in the material inventory, under consideration of the material usage per unit, is not enough material to produce with the desired production start rate, the production start rate is limited. The material delivery rate is structured similar to the production with a materials inventory and a material delivery rate as well as the material usage rate. The material usage rate depends simplified on the desired material usage rate and the material delivery rate depends on a desired material delivery rate that is determined by the materials inventory, the desired material inventory coverage and the desired material usage rate. By contrast to the expected order rate, the material usage rate can be derived by the material usage rate and desired production start rate, and do not!!! need to be forecasted. The desired material delivery rate represents the order rate of the customer [8].

After describing Sterman's supply chain model, the previous described company processes can be identified. The Master Production Scheduling as a rough planning is represented by the demand forecasting where for every period a prognosis of incoming orders is calculated. The Production Demand Planning is represented by the material delivery where the required material for the production is calculated. Finally, the Production Process Planning is represented by the productions start rate, the WIP inventory and the production rate where the detailed processes have been accumulated in Sterman's model. The Inventory Management includes the material inventory, the WIP inventory and the inventory of finished goods [8].

4. Disturbance management model

4.1. General model setup

In its preliminary setup, the System Dynamics model is based on the work of Sterman for a four level manufacturing supply chain with detailed processes for two manufacturing participants (focused companies) within the supply chain as well as a demand source downstream the supply chain and a supply source at the upstream end of the supply chain (see figure 1). In contrast to Sterman's model, the continuous model for raw material stock and finished good stock replenishment processes for both focused manufacturing companies has been modified by using discrete event points for replenishment processes. Therefore, the model was enhanced by re-order point variables for all materials inventories as well as economic order quantity and lot size calculations, based on, later on described, cost parameters. Furthermore, the safety stock has been changed from a time-based safe stock coverage variable to a target service level degree depending safety stock calculation for a more applicable model to real supply chain planning needs.

4.2. Consideration of relevant model parameters for the disturbance management simulation model

4.2.1. Integration of logistical cost and performance parameters

As an input for the above mentioned economic lot size, economic order quantity, safety stock and re-order point calculations further parameters need to be implemented. The extension by material unit prices for each inventory level, stock holding cost per material unit as well as fixed costs per material order and production setup builds the basic input for the economic lot size and economic order quantity calculation. For the re-order point calculation, variables for the mean production lead time and replenishment time as well as variables for mean demands from the downstream production or customer unit had to be implemented. In addition to these parameters and variables, the target service level degree as a further model parameter is necessary for the safety stock calculation and had to be implemented, as well. Further input variables for the safety stock calculation are described in the following subchapter. Furthermore, for the cost-based measurement of the order backlog, backlog cost per material unit and time period had to be integrated.
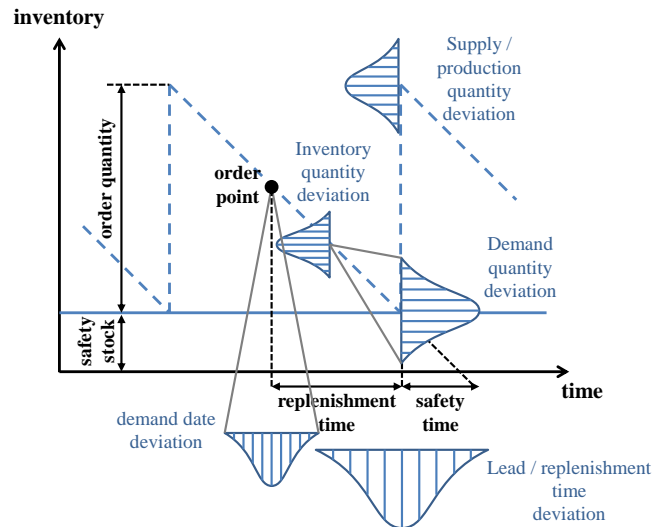
Fig. 2. Effects of deviations on the inventory management [6].

4.2.2. Integration of disturbances in manufacturing supply chains

Logistic and production-related disturbances describe a deviation from planned process workflows and results. It is of high interest to be aware of process uncertainties within a supply chain. The manufacturing company has to deal with disturbances caused by customers, e.g.., short-time orders and changes of order quantities, or disturbances caused by suppliers, i.e., deliveries with an insufficient quality and delayed or cancelled deliveries as well as with in-house disturbances. In-house disturbance arise within the manufacturing company without any external influences and reduce temporary production capacities. Reasons could be damages of production factors, machine failures or missing personal staff. Thus, these stochastic disturbances represent relevant quantity fluctuations and dispersions of time periods that can be found in the production planning and can be seen as a trigger of planning uncertainties. Uncertainties implicate a lack of adequate information with a high quality for a person, a system or an operation, so that an adequate forecast can be made. A good example is the bullwhip effect where a change in customer demands leads to higher fluctuation in demands upstream the supply chain because of the interpretation customer demands would continue increasing. Consequently, a lack of information leads to the described situation, so that an unimpeded flow of information along the whole supply chain is required. The following figure shows therefore the main effects of deviations from planned values on the inventory and consequently, the risk potential for disturbance-based process disruptions. These deviations are integrated into the model as coefficients of variation parameters (short: CV) which are defined as the ratio of the standard deviation to the mean value and lead to the deviation of mean time and quantity values for each time unit [6].

Furthermore the upstream demand quantity and especially its deviation shows a significant coherence to the single demand quantity dependency between two supply chain participants and is described by the share of the total demand of one product triggered by one single downstream supply chain participant.

4.2.3. Integration of adjustment parameters as action patterns

For the reduction of the introduced deviations and the moderation of their effects on the overall company performance additional process adjustment parameters need to be implemented as action patterns.

The adjustment of the economic lot size or economic order quantity has a significant effect on the material demand quantity and time deviation upstream. Smaller lot sizes or order quantities lead to lower deviations, but induce higher fixed processing costs.

The adjustments of the re-order points and the safety stock have on one side the effect of moderating the impacts of all kind of deviations, but lead to an higher inventory level and thus, higher stock holding costs and an higher amount of tied up capital.

The assessment of these calculation adjustments, based on cost and performance effects, will lead to the conclusion on optimal parameter setting for the reduction of disturbances.

4.2.4. Deduction and allocation of associated model parameters

Based on the further necessary parameters introduced in this work, the planning processes of the general model setup need to be extended as it is shown in the following table.

Table 1. Additional implemented model parameters.

Production process type	Reaction pattern parameters	Cost and Performance parameters	Disturbance parameters
Master production scheduling	n/a	Mean customer demand	CV of customer demand
			Demand dependency degree
Production factor planning	Economic order quantity adjustment	Mean replenishment time	CV of replenishment time
		Fixed cost per order	
		Stock holding costs per unit	
Production process planning	Economic lot size adjustment	Mean production lead time	CV of production lead time
		Fixed production set up costs	CV of production output quantity
Inventory management	Re-order level adjustment	Raw material unit value	
	Safety stock adjustment for raw materials	Finished good unit value	
	Safety stock adjustment for finished goods	Stock holding costs per unit	
		Target service level degree	
		Backlog costs per unit	

4.3. Setup of a measurement system for the impact assessment of disturbances and action patterns

For the assessment of adequate action patterns in form of the introduced calculation adjustments of order quantities, lot sizes re-order points and safety stocks the integration of a cost and performance measurement system is essential. [6] regard therefore the three target figures logistics costs, the capital lockup and the supply service level. The capital lockup represents the opportunity costs as a result of committing liquid assets in industry stocks, so that they cannot be invested on the financial market. It is measured as sum of the products of material costs and material units on stock in each time step. The logistics costs result by summing up the fixed costs for production setups and material orders as well as the unit-based stock holding and backlog costs for each time step. Backorder costs are evaluated depending on the delivery date deviation and represent penalty costs, e.g., using alternative means of transport or contract penalties, caused by a deviation from the agreed delivery date.

The supply service level measures a company's delivery performance that is defined by delivery date deviation between the agreed and actual delivery date. It arises as a result of the total material order quantity and the resulting backlog of unfulfilled order quantities. By contrast to the logistics costs and the capital lockup, the supply service level evaluates the supply chain performance. It has to be considered that these three target figures stand in a steady conflict of objectives [6].

The following figure shows the overall cost and performance measurement system implemented in the System Dynamics model.
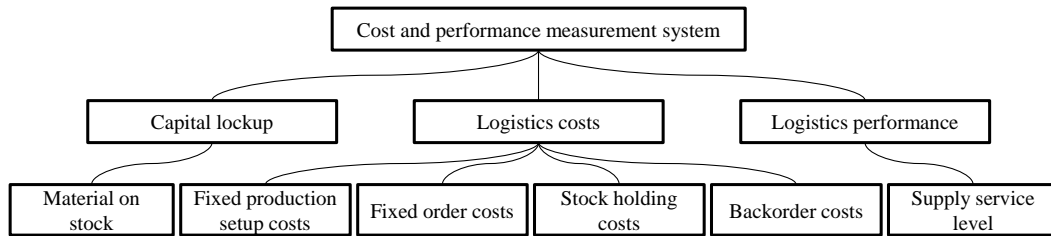
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                    ┌─────────────────────────────────────────────┐
                    │   Cost and performance measurement system    │
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Fig. 3. Cost and performance measurement system.

4.4. Testing the model

The model has been designed using the software Anylogic. This multi-method simulation modeling tool, developed by The AnyLogic Company, supports agent-based, discrete event, and system dynamics simulation methodologies.

The testing and validation of analytical model statements took place using the testing techniques described by Sterman. The boundary adequacy, the structure assessment, the parameter assessment and the behavior reconstruction is sufficiently fulfilled as the designed model bases on the tested model of Sterman and the newly introduced parameters and the measurement system, which have been described in this work refer to several preliminary works in the research area of the supply chain management. Syntax testing as dimensional consistencies and the rule out of integration errors took place using the integrated testing tools of the software.

Furthermore, extreme condition tests took place to ensure the plausibility of system responses to extreme policies, shocks and parameter values. For these test input factors and corresponding parameter settings need to be determined, which have a significant impact on the simulation model. As such input factors the replenishment time, the finished good value, the demand dependency degree and a periodical limited but significant change of the mean customer demand have been identified. The results of the extreme condition tests are assessed by the above introduced measurement system. For the plausibility check of the simulation results in each simulation run only one input factor has been changed. The following table shows the parameter settings for the input factors of the extreme condition tests.

Table 2. Characteristics of the input factors for the extreme condition tests.

Input factor	unit	Scenario 1	Scenario 2
Replenishment time	Days	3	20
Finished good unit value	EUR	5	100
Demand dependency degree	% Share of a single customer's demand	0,1	1
Change of mean demand quantity	Quantity (characteristics)	0 (-)	1 (Start: 100, End: 120; Change factor: 4.5)

All extreme condition test results reflect correctly the expected system behavior. The following figure shows therefore, as an example, the resulting supply service level degree for the demand dependency degree testing.

The test results focusing the demand dependency degree reflects the expected behaviour as a lower dependency degree to one downstream customer leads to lower demand deviations as the total demand deviation is not significantly influenced by the order policy or short-term demand changes of only one customer.

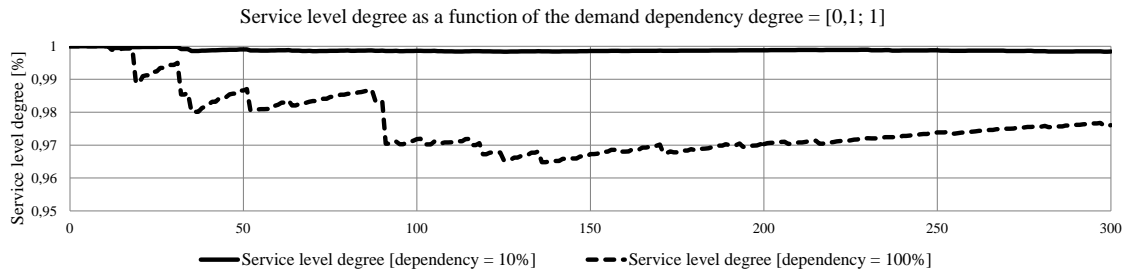Service level degree as a function of the demand dependency degree = [0,1; 1]

Fig. 4. Results of the extreme condition test for the demand dependency.

5. Conclusion and outlook

In this work an adequate extension for the manufacturing supply chain model of Sterman has been described with the target to assess the effects of disturbances and action patterns in manufacturing supply chains. Especially the extension by a system for the economical measurement of the supply chain performance, based on logistical key performance indicators, as well as the integration of additional parameters for the representation of disturbances and action patterns form the essentials of this work. The outlined testing of the simulation model validated the usability of the model for further research. Within the following steps, this model will be used for several analysis of the system behavior using the design of experiments approach. One desirable outcome should be the deduction of the interdependencies between the different disturbances and action patterns of the disturbance management as well as their effects on the key performance indicators. Furthermore, adequate access rates to disturbance information and planning parameters as well as reaction times to disturbances can be defined. Based on this outcome, optimal reaction strategies including the necessary degree of a real-time reaction with minimal delay times as well as cross-company supply strategies, resulting in higher supply chain resilience to disturbances, can be derived.

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