Technical paper

Nonlinear characterization of the performance of production and logistics networks

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A B S T R A C T

Today’s networks of production and logistics are often characterized by large structural and dynamical complexity. As a consequence of their nonlinear and potentially unstable dynamics, efficient planning and control is hardly possible, resulting in economic risks. The solution of the corresponding problems requires an overall understanding of the complex behavior of such systems. This paper uses discrete-event simulation to study networks that consist of a low number of cooperating manufacturers. The dynamics of the logistic parameters in the model are analyzed using methods originated in the theory of nonlinear dynamical systems. The results allow evaluation and potential improvement of the performance of different concepts and strategies that may be applied for the control of the dynamics of manufacturing networks.

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1. Introduction

Modern companies act on a global market, which causes them to face a large number of continuously changing challenges [7,65]. In particular, this situation requires the ability of flexible and fast adaptation to changing economic conditions, such as varying market demand for one’s own products as well as varying availability and price of commodities and further resources that are required for the production process. Furthermore, manufacturing systems or, more generally, business units are characterized by an increasing complexity due to a diversity of goods and services. In the past, many enterprises have already reacted to the corresponding requirements by concentrating on their specific core competences, incorporating concepts such as outsourcing of special tasks of production and logistics or selling well-defined production branches to other market participants. As a consequence of these tendencies, economic networks have successively developed that may span a variety of different branches of the economy.

The mutual interactions between the different companies involved in these networks, which include both cooperation and competition depending on the specific situation, can lead to very complex dynamics of the resulting networks [13,52,65]. Moreover, the combination of both diversification and specialization tendencies is known to bear a risk of severe negative effects on the particular production processes. Prominent examples for this are production breakdowns due to a lack of material as well as large and usually irregular oscillations of stocks that amplify along the supply chain. The latter phenomenon is known as the bullwhip effect [24] and has been intensively studied during the last decade [10,11,16,17,25,37,38,44,49].

To avoid such negative effects on the manufacturing process, present production systems or networks are typically controlled by sophisticated enterprise resource planning (ERP) systems [26,30,63]. In most cases, the systems are analyzed by internal and/or external experts to optimize the ongoing production processes and achieve a high degree of cost efficiency. Nevertheless, different situations can be observed in which inefficiencies of the production process still arise. In particular, due to the complexity of interactions in production systems, already small disturbances or irregularities in the delivery or manufacturing processes can result in enormous effects on downstream process variables such as irregular oscillations of stocks or an insufficient amount of available material. With conventional methods, these effects cannot be avoided even by careful planning and control.

The most common approach to address the problems mentioned above is a decoupling of the different business units. Here, large buffers are implemented to satisfy short-term demands for material that cannot be provided in time by the respective suppliers. Obviously, the availability of sufficient stocks increases the robustness of the system with respect to demand fluctuations and the bullwhip effect. However, this decoupling also has some severe disadvantages: First, high inventory levels require large initial investments. Second, large buffers correspond to the storage of...
a large amount of capital that is not available for other purposes. Finally, in the presence of large buffers the average time intervals between delivery of material and production of final goods increase. Hence, in the presence of gradually accelerating cycles of development and production, buffers with high inventory levels often denote a large economic risk, especially for smaller companies. As the alternative of smaller buffers is not well suited for balancing large and potentially unpredictable demand variations, the optimal choice of the dimensions of a buffer is a very important task for the design of production systems [5,14,46,56].

According to these problems of the decoupling strategy, companies in the real world instead tend to closely link to each other by applying strategies such as just-in-time logistics [7,28]. As a consequence, the resulting business networks may become extremely large and complex, which may again result in a very irregular dynamics.

Complex networks exhibiting an irregular dynamic behavior are not restricted to the field of production and logistics but can be found in many fields of science and technology [2,6,12,47,66,72]. For the analysis of their structural as well as functional properties, two different approaches are possible: the consideration of the networks as stochastic systems in terms of concepts taken from the theory of statistical mechanics, and a nonlinear dynamics point of view. For the latter approach, the dynamics of the networks are considered as a result of interactions of deterministic dynamical systems. If these interactions of different components are nonlinear, chaotic dynamics may arise even without a large structural complexity of the network [8,29,33,34,50,54,70,71]. Whereas traditional statistics usually are not able to distinguish between stochastic and deterministic-chaotic behavior, over the last decades a number of novel concepts has been developed that may be used to appropriately characterize the dynamical state of a system [1,31,64]. Nowadays, there are various methods in nonlinear time series analysis that not only allow distinguishing between chance and chaos but also characterize the chaoticity and/or stochasticity in a quantitative way.

In the case of real-world networks of production and logistics, there are, however, a very large number of relevant state variables with a nontrivial mutual interdependence. Moreover, structural features and discrete-valued logistic observables such as stocks change very frequently. This setting requires a careful choice and possibly adaptation of existing as well as the development of novel innovative methods for the modeling, analysis, and control of such networks using conceptual approaches originated in the theory of nonlinear dynamical systems. Such methods not only help to cope with but actually take advantage of the complex dynamics in order to achieve logistic goals such as low inventory levels, short throughput times, and high degrees of reliability that are necessary for an optimized performance of manufacturing networks [5,52].

To optimize the performance of networks of production and logistics in terms of low inventory levels, low throughput times, or high reliability of deliveries, a careful investigation of the essential mechanisms that determine the system dynamics is necessary. As the amount of available information about the dynamics of real-world manufacturing networks (in particular, time series of logistic observables) is usually rather limited, it is suitable to first map the essential processes of manufacturing and logistics into an appropriate mathematical model, which can then be used to simulate ensembles of independent realizations of the dynamical evolution of the system. For this purpose, different approaches are possible. To analyze the general features of manufacturing networks, continuous-flow or discrete-event models can be studied that represent the essential structures of interactions in the underlying systems on a very abstract level. This work focuses on discrete-event simulation models. In contrast to time-continuous models, within discrete-event simulations the changes of the status of the relevant state variables take place at discrete times and are caused by atomic events that themselves do not require any time. In the case of such an event-controlled simulation, the state of the system does not change between two sequential events. For this reason, it must be certain directly after an event which event takes place next and at which time. An example of such a discrete event is the arrival of a workpiece at a processing machine. Discrete-event simulation is an exact approach [4] with high-detail complexity [45]. As every object is modeled individually [3], typical areas of application are on the level of production lines [36]. For more extensive modeling tasks such as the simulation of whole delivery chains, discrete-event simulation is less suitable because the high computational capacities required lead to a substantial slowdown of the simulation [4,36]. According to this, the time horizon of discrete-event models is concentrated within the operational range, whereas the continuous modeling approach covers the strategic time horizon [45].

The use of general modeling approaches such as continuous-flow or discrete-event simulation is often not efficient for examining the dynamics of a particular real-world network of production and logistics in some detail. As an alternative, there are several well-developed software packages that allow mapping of specific network structures and analyzing their performance systematically. The implementation of the corresponding models using these packages allows the identification of economic potentials and a successive test of various optimization and control strategies.

In the literature, several approaches can be found for the modeling and analyzing of manufacturing systems with methods of nonlinear dynamics, which shall be briefly summarized in the following. Chase, Serrano, and Ramadge [8] used a switched-flow system for the description of a certain machine and buffer arrangement in a production system. They examined the dynamics of the receiver system by means of the trajectories in the state space and demonstrated the existence of chaotic behavior. Katzorke and others [32–34,50] described this discrete event controlled receiver system by means of a strange billiard that exhibits chaotic dynamics. Controlling the system by means of the well-known OGY method [48] was proven to minimize a certain cost function of the production process. Rem and Armbruster [54] extended the same system by implementing switching and maintenance times. Wiendahl et al. [51,73,74] defined maximum buffer capacities whose reaching leads to a change of the server, demonstrating a similar complex dynamics as in the original work of Chase, Serrano, and Ramadge [8].

Tönshoff and Glöckner [68] used a continuous-flow model for describing the flow of material in a workshop by means of a funnel model. Their simulations with multiple parameter combinations revealed again a rich variety of different dynamical behavior, which was not necessarily chaotic in every case. Scholz-Reiter and Nathansen [57] and Scholz-Reiter and Freitag [58] presented several further examples of chaotic phenomena in production systems. For the control of irregular fluctuations in the stock values, the applicability of different chaos control methods was tested. In addition, special methods for the analysis and control of complex inhomogeneous systems with nonlinear and/or time-delayed couplings were developed. However, despite these numerous approaches, there is still hardly any systematic understanding of the whole variety of dynamical behavior of production systems. In particular, existing methods for evaluating the performance of manufacturing networks subjected to different types of control strategies still need to be significantly improved or extended in order to develop a holistic framework for characterization and control of such systems. The approach presented in this paper is based on the analysis of time series of logistic quantities by methods originated in complex systems
sciences and allows the nonlinear quantitative characterization of the observed dynamics as well as the evaluation of different control strategies.

To improve the general understanding of the fundamental mechanisms that determine the dynamics of manufacturing networks, considered in the following is a discrete-event model of a network of production and logistics that consists of four collaborating companies. This setting has been chosen to examine the dynamical meaning of a relatively small number of fundamental parameters for the performance of the production process. Moreover, in the case of manufacturers with a rather specific range of products, it is very likely that both the size of the production network itself as well as the number of external suppliers and customers are restricted. A recent contribution [61] already started to study the nonlinear dynamics of this system in the presence of different order policies. The present work will extend the corresponding investigations by an application of additional sophisticated methods of nonlinear time series analysis.

The new results yield a fundamentally deeper understanding of the complex behavior of stock variations in manufacturing networks and allow the systematic evaluation and comparison of different control strategies.

The details of the model are described, followed by a qualitative evaluation of the nonlinear dynamics of this system, focusing on the influence of different order policies on the variations of the inventory levels (stocks) as a logistic quantity of special interest. This analysis is extended by a quantitative characterization of the regularity of the observed dynamics. For this purpose, two approaches from nonlinear time series analysis briefly are introduced as particularly well suited for studying discrete-valued time series such as stocks: symbolic time series analysis and recurrence quantification analysis. Time series obtained from the model under different order policies are successively studied by these methods to characterize the effects of the specific settings. Finally, some possible strategies are discussed for a more efficient management of networks of production and logistics with respect to the results of the model simulations.

2. Model description

For the implementation of the model network, the discrete-event simulator eM-Plant 7.5 (Tecnomatix Technologies Ltd.) was used. The following describes the basic features of this model and its different variants used in the simulations to examine the dynamical effects of different parameters as well as control strategies.

2.1. Basic model features

Attention is focused on a rather small-scale network model, which includes four manufacturers that can be considered as the nodes of this network. Due to this rather small number, possible feedback in the network can arise relatively fast, which allows an efficient investigation of the different instabilities that may occur in this kind of system. All nodes in the model are firmly connected via predefined supply lines. The underlying dynamics are determined by a basic clock controlling all activities, which is set to a value of one hour in all simulations.

Every manufacturer is represented by a submodel that includes the actual network-internal procedures (see Fig. 1). For simplicity, the basic structures of these submodels are identical for all manufacturers. Each node consists of four production lines (which correspond to the total number of manufacturers) and is therefore able to simultaneously manufacture four different products. In addition, every node has four sort-pure buffers (that is, buffers that contain only one specific commodity) for four distinct types of semi-finished material whose sizes are not limited and that can be assessed by all production lines. One of these buffers is equipped by a network-external supplier, while the remaining ones are supplied by one specific production line of each of the other nodes in the network via predefined connections. Whereas the corresponding goods stay inside the network and are used as semi-finished material by the other collaborators, the remaining product of every manufacturer is supplied to a network-external customer. To keep this supply scheme as simple as possible, each supplier inside or outside the network delivers only one sort of semi-finished material to the respective customer.

To pass a possible transient phase after the initialization of the simulation, nonzero buffer sizes are prescribed at the beginning of each simulation. To start the fabrication of a product, certain kinds and numbers of semi-finished materials are required. The corresponding combination is defined in a designated production matrix.

All production and delivery events that take place in the model are modeled in terms of time-discrete events. The fabrication of the products only starts when the appropriate production factors are present in sufficient quantities. For the realistic illustration of the production process, operating times and working-on intervals have been implemented into the model. This setup allows an explicit computation of the time required for completing a product and to permit or prohibit a multiple treatment of the production lines. By prescribing different lot sizes in the production matrix, it is possible to consider different scenarios that correspond to different capacities of transport containers. Deviating transportation routes with different lengths can be modeled by prescribing the transportation times. Further parameters of the model are: order points, order intervals, order volumes, and buffer sizes at the beginning of each simulation run. For an accurate control of the supply of the semi-finished materials from outside the network, all mentioned parameters can also be defined for the external suppliers.

To be able to analyze the effects of the different parameters in the model, appropriate evaluation interfaces have been implemented into the model. At the beginning of every simulation period (that is, in every discrete time step of the model), the current stocks within all buffers are recorded. To early-detect strong, irregular fluctuations in these buffers, the data are additionally displayed visually. A further evaluation possibility for all production lines is provided by charting the time intervals between two production events, which can be visualized in a similar way.
2.2. Model variants

To evaluate the dynamic effects of different control strategies, order policies, and parameter settings on the performance of the considered manufacturing network, several variants of the model described above have been studied. Besides the variation of the model parameters already mentioned in the previous section and listed in the Appendix (that is, operation times necessary for processing a given product, transportation times, working-on intervals, lot sizes, and initial buffer sizes), these variants include: 

Strategies for production control. The most general strategies for the control of production processes are push and pull strategies.

In the case of pull control, in the model each manufacturer wants to first fabricate the product that is supplied to the external customer (that is, removed from the network) in every production period. If semi-finished material of all necessary kinds is not available in a sufficient quantity, production orders according to the necessary lot size are sent to the respective suppliers. These orders are inserted in the company-internal production plan and processed in the next period. If the buffers are sufficiently filled, the requested semi-finished material is fabricated and dispatched in addition to the final product for the external customer. If the available stocks are not sufficient for the production of semi-finished material, production orders are initialized in the same way as before. In the case of symmetric interactions between all network participants studied in this manuscript, this procedure can continue up to the original client, which may then become its own supplier.

In contrast to the pull strategy, in the case of push control every manufacturer wants to fabricate both the final product and the material from the respective suppliers. This study has considered the three simple approaches: provision, order point, and periodic order policies.

The provision policy is based on the kanban principle and is characterized by some sort of self-regulation. The detailed customer orders are seized and processed. If an appropriate stock is available, a delivery of the required amount of products takes place. Subsequently, it is checked whether there are still goods in production or not. If this is not the case, the goods from the buffer are brought into production, and the corresponding supplier receives a notification that a provision unit must be supplied.

In the case of an order point policy (s, q-policy), the point in time at which an order is placed is determined by the order point, s, while the order volume, q, is constant. The available stock levels are permanently compared with the actually reported stock levels. A shortfall of the actual stock level below s leads to an immediate order with a fixed quantity, q. With this procedure, it is guaranteed that the material is available exactly when the safety stock level is reached.

For a periodic order policy (s, S-policy), the ordering time is also strongly influenced by the ordering point, s (see s, q-policy), while the order quantity, S, is variable and depends on the actual stock level. The order quantity is computed from the difference between the desired stock level and the actually available stock level. It is possible to refine this policy by introducing an interval, r, which sets the time span between two comparisons of the actual and the desired stock level (r, s, S-policy). If r equals 0, the actual stock levels are checked permanently. For this work, the r, s, S-policy [46] was used.

In contrast to a push strategy, the consideration of a pull control or the corresponding more sophisticated order policies described above yields additional model parameters that are specific for the respective policies, in particular the order volumes, the critical stock levels, and the time intervals in which the available stocks are checked. The problem of demand forecasting or anticipation is not discussed here, which is surely another extremely critical point for the performance of real-world networks of production and logistics [60].

A more detailed mathematical description of the considered simulation model as well as the aforementioned order policies is given in Donner, Hinrichs, and Scholz-Reiter [20].

Besides control strategies and order policies, different other properties can be varied:

Different network sizes. Similar to the model considered in this article, a structurally equivalent network consisting of only two collaborating manufacturers has already been thoroughly studied [18,19,59]. In the presented work, the corresponding results will only be briefly summarized. Other network sizes may be considered as well.

Deterministic and stochastic event times. In the basic case of fixed event times, all time scales of the model are prescribed to constant values that do not change with time. Operation times, transportation times, and working-on intervals are multiples of the basic clock rate of the system. To additionally study the influence of stochasticity on the system’s dynamics, all time scales can also be set to be stochastically (Gaussian) distributed with the average values corresponding to those of the deterministic case and the respective standard deviations being additional parameters. In the studies of the corresponding two-manufacturer system, it has already been reported that random deviations of the event times from the deterministic clock rate lead to an immediate instability of the regular deterministic dynamics, which manifests in terms of a very irregular behavior of the stocks where eventual periodic components are completely lost instantaneously [18,59].

Static and dynamic demand. In the case of a pull control, the demand of the external customers can either be constant in time or vary following a predefined deterministic or stochastic function. The demand of the network-external customers for the products is a main factor for the emerging dynamics in the modeled network of production and logistics. A static external demand represents a market for goods that does not undergo strong random or seasonal fluctuations, for example, due to changing weather conditions. For the representation of a dynamic demand, a periodic function \( d(t) = A \cos \pi t / T \) is chosen for modeling a market with seasonal demand fluctuations because it yields a rather simple approach to generate additional dynamics in the model. A more general or even stochastic variability can also be prescribed but has not been used in the presented study.

Finally, it has to be mentioned that the simulation model can be easily adapted to other network topologies, including linear supply chains, as well as interaction patterns with a complexity between a linear chain and a complete symmetric coupling. However, a discussion of the corresponding effects is beyond the scope of this paper.

3. Nonlinear dynamics of the model: Qualitative analysis

As the interactions between the different manufacturers in the model are already rather complex and determined by a relatively large set of parameters, it is not surprising that this system shows a variety of different dynamical patterns. Indeed, this is already the case for the less-complex two-node version of the model [18,59].
In particular, if the material flows in the network are balanced in terms of lot sizes and intrinsic time scales, the system is stable if the basic time intervals are constant. In the case of a push control, the corresponding dynamics of the stocks are remarkably stronger than for a pull control. However, if one of these premises is violated, it has been shown that different dynamic instabilities may occur whose reasons can be clearly distinguished [19]:

Fluctuating production intervals: As has already been mentioned in the previous section, random influences, which are typically present in real-world manufacturing networks and change the actual length of production and/or transportation times, have an instantaneous destructive effect on the logistic performance and lead to intermittent time intervals of accumulation of material or unprocessed orders. The corresponding effect does not depend on the particular strength of stochasticity over a certain range of moderate standard deviations of the event time distributions. Whereas the accumulation effect is rather moderate and almost equally distributed over all buffers in the case of a pull strategy, under a push control those buffers that are equipped by external suppliers show low and stable stocks, while those that contain semi-finished material delivered from other manufacturers within the network are filled much faster than in the case of a pull control.

Imbalance of material inflows and outflows: In the presence of a push control, for large working-on intervals the stocks of semi-finished material may increase beyond acceptable limits. In contrast, in the case of a pull control this effect is absent as the balance between production and material supply is provided here by appropriate sizes of orders. If in the case of an unstable push system, stochasticity is added to the model in terms of distributed production intervals, the severity of this instability (that is, the velocity of material accumulation) was found to decrease in the two-node system, where the slope of the remaining increase of the inventory levels was found to crucially depend on the model parameters, but hardly on the standard deviation of the stochastic component.

Incomplete logistic synchronization: In the case of a pull control, an improper choice of lot sizes increases the complexity of the manufacturing network in a way that the strict periodicity of the production process in the case of fixed production intervals may be lost. However, in contrast to the accumulation instability described above, the inventory levels remain bounded on rather low levels. The results of symbolic time series analysis [59] suggest that the change in the corresponding dynamics is associated with additional frequencies, resembling the transition from fully periodic over quasi-periodic toward chaotic states in nonlinear systems. However, the detailed mechanism of this instability is not yet fully understood [19].

In comparison to the two-node network, the consideration of the four-node version of the model allows an even deeper insight into the variety of possible dynamics that can be observed in small-scale networks of production and logistics. The following is mainly restricted to one specific setting where all characteristic time scales have been chosen to be equal throughout the whole network. A full list of model parameters and their values in the considered setting can be found in the Appendix.

To evaluate the overall performance of the model, first are discussed the general dynamics as well as the distribution of typical values of the stocks in the presence of different order policies and demand dynamics. Figs. 2 and 3 show the results of some simulation runs for static and periodic demand, respectively. First of all, one may recognize that there are still long initial transients, which may last up to 10,000 simulation periods or even longer (only for a periodic order policy, the asymptotic dynamics of the system is reached significantly earlier). For the order point policy, a high degree of regularity is found, which manifests itself in a stable long-term periodicity of the stocks. For the two other policies, a corresponding periodicity is clearly less pronounced, while much higher inventory levels may be observed in some of the buffers. In particular, for the provision policy, a remarkable long-term behavior is observed with a fast accumulation of material that is followed by a significantly slower successive decrease of the buffer levels. Note, however, that in contrast to the other order policies, the typical time scale of these slow dynamics involves several thousand simulation periods, which is far more than in the case of the large-scale fluctuations for the order point as well as periodic order policies. Finally, in the case of the periodic order policy, the initial transient behavior seems to be much shorter than for provision and order point policies. A possible explanation is that there are no fixed intervals of orders, such that variations in the actual demand are balanced more efficiently.

To further characterize the behavior of the inventory levels in the presence of different order policies, their probability density functions have been explicitly estimated for both a static and variable demand in terms of the relative frequency of occurrence of the different possible values in the inventory time series of the simulations. The corresponding results shown in Fig. 4 are found to be consistent with the previously reported results. In the case of the provision policy, it is found that the stock distributions are very robust with respect to variations of the demand as well as of the different model parameters. However, this robustness comes at the cost of a large remaining probability of very high stocks. An order point policy yields the lowest inventory levels for those buffers that are equipped by external suppliers. In contrast to this observation, the other buffers may show higher inventory levels, which may cause severe effects especially in the case of temporal variations of the demand (see Figs. 2 and 3). A detailed quantitative assessment of this sensitivity has been beyond the scope of the presented study but is certainly an important question in real-world production systems. As a compromise between both extreme cases, the periodic order policy leads to the lowest stocks in those buffers that contain semi-finished goods delivered from the collaborating companies (see Fig. 4). In addition, under this policy, variations of the demand do not increase the stocks but lead to even a decrease of the average buffer levels. The mentioned general features are qualitatively robust under variations of the main model parameters.

4. Quantitative analysis of network dynamics

The previous section considered only the large-scale features of the stock variations, that is, the existence of low-frequency periodic components (that is, regular components with periods of several hundred to thousand simulation steps) and the probability of very large stock values. With respect to the probabilities of large fluctuations of the inventory levels, the periodic order policy seems to be the best order strategy in the case of a more realistic variable market demand. This analysis, however, reflects only the basic statistical features of the model.

To achieve a more detailed quantitative assessment of the major dynamical features of the inventory levels, sophisticated methods of time series analysis should be applied. Traditional approaches from this perspective include mainly linear methods such as correlation functions or spectral (Fourier) analysis. Especially the latter concept is of interest when searching for hidden periodicities or certain scaling properties within a time series (given its stationarity). In contrast, this study is more interested in features characterizing the regularity of the production process, so that Fourier analysis is not necessarily an appropriate tool. Moreover, note that Fourier as well as traditional correlation analyses have been invented for studying quantities with a continuous range of values, whereas this range is discrete for inventory
levels. According to this, the application of nontraditional time series analysis techniques seems to be more promising. In particular, methods designed for integer values and possibly nonstationary data from nonlinear dynamical systems appear to be more reasonable candidates for characterizing regularity and predictability of stock fluctuations in a quantitative way.

The following shows how two particularly suitable concepts of nonlinear (that is, complex systems based) time series analysis can be applied to characterize the dynamic complexity of inventory-level data in more detail: symbolic time series analysis and recurrence quantification analysis. In both cases, the focus is mainly on the short-term dynamics of the stocks that contain essential information about the regularity of the model behavior. A recent work \[61\] reported some preliminary results of the corresponding investigations using symbolic time series analysis. However, the presence of long initial transients has not yet been explicitly considered. In the following, all information from the first 10,000 (provision and order point policy) and 2000 (periodic order policy) simulation periods will be excluded, respectively, in order to avoid artifacts due to the presence of such transients. For a more detailed quantitative characterization of the nonlinear dynamics, the application of recurrence quantification analysis as a complementary tool will be additionally discussed.

4.1. Symbolic time series analysis

The concept of symbolic dynamics \[55\] has been originally developed for characterizing the properties of a dynamical system exclusively based on its topology by a partitioning of its phase space, which yields a transformation of every possible trajectory into an infinite sequence of abstract symbols. The
formal applicability of this framework requires the existence of a generating partition that corresponds to a unique assignment of symbolic sequences to any trajectory of the system. Whereas such optimal partitions usually exist for deterministic model systems, for time series of finite length (which represent trajectories of the underlying dynamical system) with eventual noise, generating partitions either do not exist at all or can hardly be estimated (see Hirata, Judd, and Kilminster [27] and references therein).

Disregarding these conceptual difficulties, the fact that observational time series are often contaminated by noise has motivated the idea that a reduction of the corresponding data to their basic topological patterns can be achieved by means of coarse graining. Such a coarse graining is formally equivalent to a symbolic encoding and suggests the systematic application of methods of symbolic time series analysis [15]. Apart from the reduced influence of observational noise, the efficiency of the computation of different measures may be significantly enhanced by this approach.

There are different ways to realize an appropriate symbolic encoding: A static encoding considers one or more threshold values and thus discretizes the range of possible values into disjoint classes. Hence, this kind of coarse graining of the dynamics leads to symbolic sequences that mainly contain the essential large-scale dynamics of the system. Applying a similar thresholding to a difference-filtered time series (that is, the increments of the original data, in this case the variations of the inventory levels) yields a dynamic encoding, which contains hardly any information.

Fig. 3. Same as for Fig. 2, for periodic demand variations.
about the long-term variations but preserves the essential short-
term variability. Under rather general conditions, mixed forms
of both major strategies may be applied as well [20]. This work
will exclusively consider a dynamic encoding that maps the time
series \((X_t)(t = 1, \ldots, T)\) into a symbolic sequence \((x_t)\) where the
symbols \(x_t\) have been taken from the three-symbol alphabet \(A = \{-1, 0, 1\}\). In particular, \(x_t = 1(0, -1)\) if \(X_{t+1} > X_t (= 0, < 0)\).

The probabilities and joint probabilities, \(P\), of different symbols,
s, as well as \(n\)-block sequences, \(s^{(n)}\), within the symbolic time series
may be used to compute a variety of statistical measures. As a
particular example, the symbolic correlation function, \(C_{XY}(\tau)\), will
be considered that quantifies the strength of linear dependences,
\(Y(t + \tau) = \alpha X(t)\), between two time series, \(X\) and \(Y\) [39].

\[
C_{XY}(\tau) = \sum_{s \in A} P(x_t = s \land y_{t+\tau} = s).
\]

For time series whose range of possible values is restricted to
a small discrete set (which is the case for stock fluctuations),
the use of this function may be superior to a consideration of the
standard correlation function, which is more efficient in the case
of continuously defined variables.

As a nonlinear generalization of \(C_{XY}(\tau)\) that characterizes the
strength of a general dependence, \(Y(t + \tau) = f(X(t))\), between
both data sets, the corresponding mutual information, \(I_{XY}(\tau)\) [41],
will be additionally studied.

\[
I_{XY}(\tau) = \sum_{s, s' \in A} P(x_t = s \land y_{t+\tau} = s') \log \left( \frac{P(x_t = s \land y_{t+\tau} = s')}{P(x_t = s)P(y_{t+\tau} = s')} \right).
\]

As this measure is (like a covariance function) not a priori
normalized, a normalized version will be applied that is defined
following the transformation between covariance and correlation
function, that is,

\[
l_{XY}(\tau) = \frac{I_{XY}(\tau)}{\sqrt{I_{XX}(0)I_{YY}(0)}}
\]

with \(l_X(0) = l_{XX}(0)\) and \(l_Y(0) = l_{YY}(0)\). Here are given the
equations for the bivariate case with two time series, \(X\) and \(Y\),
without loss of generality, as the expressions for the univariate case
(that is, the autocorrelation function and autocorrelation function,
respectively) follow directly with \(X = Y\). In the following,
attention is restricted to the latter case as autocorrelation and
autocorrelation function carry essential information about the
dynamics of inventories stored in the individual buffers of the
considered production system. A detailed evaluation of the
dynamical meaning of mutual interdependencies between
different buffers (which is surely important for a fundamental
understanding of the mechanisms controlling the dynamics of
manufacturing systems) is outlined for future studies, including
further examinations of the two-node system in which the
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understanding of the mechanisms controlling the dynamics of
manufacturing systems) is outlined for future studies, including
further examinations of the two-node system in which the
corresponding interactions can be investigated more easily.

To extract further information about the nonlinear behavior,
one may estimate the entropy of the underlying system that
quantifies its disorder or, equivalently, the lack of information
about its dynamical behavior as a characteristic measure of the
complexity of the dynamics. A convenient way to approximate
this quantity is to consider the limit of the conditional block entropies,
\(h_n\), of symbolic sequences, \(x^{(n)}\), with length \(n\) [21], which are
defined as \(h_n = H_{n+1} - H_n\), where

\[
h_n = - \sum_{x^{(n)} \in A^n} P(x^{(n)} = s^{(n)}) \log P(x^{(n)} = s^{(n)})
\]
is the Shannon entropy that measures the average amount of information of n-block sequences within the symbolic time series. Like the symbolic correlation and mutual correlation functions that have already been used to study the dynamics of the two-manufacturer model [18,59], the concept of entropies has also recently been applied in the context of the performance of production systems to evaluate the general predictability of different simulated and real-world demand patterns [60]. The following goes beyond these preliminary results by successively applying both kinds of concepts to a systematic investigation of the performance of the four-manufacturer network.

4.2. Regularity and complexity

As all time scales of the model (in particular, processing and transportation times) have been kept constant in the presented simulations, there is no instability due to stochastic fluctuations of the production process. Nevertheless, the dynamics of the considered network are already very complex.

For investigating the effects of different order policies in some detail, the symbolic autocorrelation as well as automutual information functions were first computed. The corresponding results for the externally equipped buffer of the first manufacturer in the model are shown in Fig. 5. In general, it is found that the symbolic correlation functions do not decay to values near 0, while a corresponding decay is observed in the case of the mutual information. Whereas the actual presence of strong linear correlations would necessarily result in high values of the mutual information as well, this finding therefore clearly indicates that there are no important linear temporal interdependences except a periodic component, which will be further examined next. Thus, the estimated values of the symbolic correlation functions can only be explained by a large bias due to the specific choice of the symbolic encoding. Indeed, it is known that the corresponding amplitudes may crucially depend on the specific encoding such that a quantitative interpretation is problematic. In particular, for the symbolic mapping used above, the symbol \( x_t = 0 \) occurs significantly more often than the other two, which may be the main cause of the observed bias. However, to extract only qualitative features of the considered time series, such as the existence of periodic components, the consideration of these quantities seems still to be appropriate.

In the case of provision and order point policies with fixed order intervals, both symbolic correlation and mutual information functions suggest the existence of a strong periodic component that corresponds to the time intervals in which the fixed amount of material is ordered (six simulation periods). The decay of the successive maxima of \( C_X(\tau) \) strongly resembles the instability of the two-manufacturer system under a pull strategy, which has been explained by an increased complexity of the dynamics due to incomplete logistic synchronization [18,19]. It will be subjected to further research about whether complete logistic synchronization is possible at all with the applied order strategies and for more than two manufacturers.

If the periodic order policy is applied for placing orders of an appropriate lot size, there is no fixed size of orders. As a consequence following from Fig. 4, the resulting periodic component of the dynamics is significantly weaker than for the other two policies and shows variations with the highest possible frequency. Comparing the probability of different symbols within the encoded time series (see Table 1), one finds that for the periodic order policy 0 occurs much less often than in the other cases, indicating stronger dynamics on short time scales. Hence, it is not clear whether a quantitative comparison of the corresponding symbolic correlation as well as mutual information functions for all three order policies can lead to reliable results. Consequently, the focus here is on an analysis of the qualitative findings.

Apart from the existence of some distinct periodic components, the underlying decay of symbolic correlations as well as mutual information indicates a remarkable deviation from a fully periodic behavior. Moreover, as a general feature shared by all studied policies, the qualitative behavior of the inventory levels remains similar if a static demand is replaced by a periodic one. To further characterize the dynamic complexity of the model, the behavior of the conditional block entropies, \( H_m \), with varying sequence length, \( n \), have been studied. Due to the periodicity under provision as well as order point policies with a period of six time units (hours), the entropies show a significant decrease before they saturate at \( n > 6 \) (see Fig. 5). For the provision policy, the values may slightly vary between the different production lines, while they become almost equal in the order point policy. The quantitative differences between static and dynamic market demand are again negligible.

For the periodic order policy, the scaling of the entropies supports the observations obtained from the correlation functions. As there is no intrinsic fixed periodicity of orders, the entropies remain significantly decreasing also for \( n > 6 \) and do not show saturation in the considered range of \( n \). In general, the much larger values of the entropies may suggest that the conditions under a periodic order policy may be more complex than in the other two cases. However, it has to be stressed that the numbers are not necessarily comparable here, as they may be crucially affected by the frequency of the individual symbols, which remarkably differs between the individual policies (see Table 1). The same holds for the comparison between static and periodic demand conditions, although the dynamics are typically more complex in the case of a periodic demand (see Figs. 2 and 3). As follows from a comparison of both figures, for the case of an order point policy, more complex does also mean less stable; that is, temporary accumulation of large amounts of material may be observed.

4.3. Recurrence quantification analysis

The previous considerations have demonstrated that statistical quantities based on symbolic time series analysis allow a reasonable characterization of dynamical systems. The use of these quantities adds an overall value to the quantitative accessibility of the performance of manufacturing networks in the presence of different order policies in terms of regularity and the presence of periodic contributions to the dynamics of these systems. In particular, an additional symbolic encoding has been used that leads to a dramatic decrease of the required computational efforts compared to a direct estimation from the data (which is possible in the case of integer-valued time series).

Although the presented results appear to be reasonable, the symbolic dynamics approach also has some severe disadvantages. As has already been argued, the estimated values of the corresponding measures may crucially depend on the appropriate definition of symbols, especially regarding their statistical distribution. It has been shown in the example that this holds especially for the symbolic correlation functions, which show a particularly artificial behavior. However, careful analysis by means of extensive simulations has shown that the estimated values of mutual information [9,35] as well as entropies [23,62] based on symbol sequences may show a similar dependence on the symbolic encoding [20].

As an additional problem, the computation of block entropies for large block lengths, \( n \), or larger alphabets is computationally extremely inefficient. In particular, the number of possible sequences, \( 2^m \), and, consequently, that of the computation steps required for the calculation of the corresponding block entropies, \( H_n \), increases exponentially with the block length. As the entropy of the underlying system is an asymptotic property of the differences
Fig. 5. Symbolic autocorrelation functions $C_X(\tau)$ (upper panels), normalized automutual information functions $I_X(\tau)$ (mid panels), and scaling of the conditional block entropies, $h_n$, with the word length, $n$ (lower panels), of the inventory levels of an externally equipped buffer under order point (solid), periodic order (dashed), and provision policy (small circles).

Table 1
Relative frequencies of the different symbols $x_t = (-1, 0, 1)$ for the first two buffers of the first manufacturer.

<table>
<thead>
<tr>
<th>Buffer 1 (external supply)</th>
<th>Static demand</th>
<th>Periodic demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P(x_t = -1)$</td>
<td>0.0076</td>
<td>0.0055</td>
</tr>
<tr>
<td>$P(x_t = 0)$</td>
<td>0.9202</td>
<td>0.9545</td>
</tr>
<tr>
<td>$P(x_t = 1)$</td>
<td>0.0722</td>
<td>0.0400</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Buffer 2 (internal supply)</th>
<th>Static demand</th>
<th>Periodic demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P(x_t = -1)$</td>
<td>0.0070</td>
<td>0.0052</td>
</tr>
<tr>
<td>$P(x_t = 0)$</td>
<td>0.9722</td>
<td>0.9707</td>
</tr>
<tr>
<td>$P(x_t = 1)$</td>
<td>0.0208</td>
<td>0.0241</td>
</tr>
</tbody>
</table>

in the block entropies, it can only be roughly estimated using relatively small block lengths.

As an alternative that is computationally less demanding and may also be applied in the case of nonstationary time series, one may use the so-called recurrence quantification analysis (RQA). This approach is based on a quantitative assessment of recurrence plots, which have originally been developed as a visualization tool for the recurrences of the trajectories of a given dynamical
system in some appropriately defined phase space [22]. The idea behind this concept is a comparison of the differences of the values of a specific observable at any pair of observation times \(t, t'\), with a prescribed threshold, \(\varepsilon\). A graphical representation of the recurrence pattern is then obtained by a static binary encoding of this difference in terms of the recurrence matrix

\[
R_X(t, t') = \Theta(\varepsilon - |X(t) - X(t')|)
\]

where \(\Theta\) is the Heaviside function, which yields a value of 1 if the values of the variable \(X\) at times \(t\) and \(t'\) are “similar” (with a distance less than \(\varepsilon\)) and 0 otherwise. If the entries of this binary matrix are visualized by black (1) and white (0) squares, respectively, the resulting graphical representation can be easily interpreted in terms of deterministic dynamical structures. For example, a periodic signal would result in equally spaced diagonal structures in the recurrence plot, whereas random signals would lead to a plot not showing any substantial structures. In the case of high-dimensional deterministic signals, one may observe interrupted diagonal as well as vertical lines. Finally, trends in the data lead to a loss of recurrence; that is, the number of recurrent pairs of observations decays with their temporal distance. For a more detailed review on this qualitative interpretation of recurrence plots, see Marwan et al. [43]. In the case of the manufacturing network studied in this paper, it can be clearly seen by comparing Fig. 5 with the associated parts of Fig. 2 that imperfect long-periodic components are frequently recovered in terms of interrupted diagonal structures, whereas short-term periodicities seem to occur only intermittently, which leads to the formation of cluster-like quadratic patterns in the recurrence plots.

Besides its meaning as a visualization tool, recurrence plots may be used to estimate several nonlinear dynamic characteristics. The idea of this recurrence quantification analysis (RQA) has been originally introduced by Zbilut and Webber [75] and since then has been continuously extended (see Marwan et al. [43] for a detailed review). It is based on the computation of certain sophisticated (mainly nonlinear) statistical properties of the distributions of continuous diagonal \((t - t' = \text{const.)}\) or vertical \((t = \text{const.})\) structures in the corresponding recurrence plots [42,69].

One of the most traditional nonlinear quantities that can be estimated in terms of RQA is the Shannon entropy of the underlying system. Recently, it has been demonstrated that although this estimate is less sensitive with respect to the complexity of the recorded dynamics than the one based on symbolic encoding, it is more robust in the presence of stochastic contaminations that are typically present in real-world systems [40]. Moreover, the consideration of a recurrence plot based estimate does not require the choice of one specific symbolic encoding of the dynamics, which has been identified as the major source of problems in applications of symbolic time series analysis.

In addition to the possibility of directly computing an estimate of the Shannon entropy, generalizations of the other measures from symbolic time series analysis introduced in the previous sections can be estimated as well. Instead of the symbolic correlation function, a generalized correlation function may be computed based on the density of recurrent points on the diagonals of a recurrence plot. In a similar way, instead of the “ordinary” mutual information, the so-called generalized mutual information of second-order as well as the second-order Rényi entropy can be computed where the Shannon entropy terms in Eq. (2) are replaced by the corresponding Rényi entropy [67]. For details about the definition and estimation of these quantities, readers are again referred to the excellent review of Marwan et al. [43].

In addition to the aforementioned dynamical invariants, RQA yields a variety of additional measures that further characterize specific aspects of the regularity of the recorded dynamics. Table 2 gives the values for some of these measures, which have been computed from the part of the records shown in the recurrence plots in Fig. 6. Among others, the determinism and the laminarity (which are defined as the percentage of recurrent points that are captured in noninterrupted diagonal and vertical structures, respectively) of the inventory levels indicate an almost completely deterministic behavior as expected, while the values for the periodic order policy are slightly lower than for the other two policies. To clearly discriminate between the different situations, the mean diagonal length and the trapping time (mean length of vertical structures) are particularly well suited. The corresponding values are consistent with the number as well as size of pseudo-clusters in the recurrence plots shown in Fig. 5. In particular, the duration of recurrence intervals of the stock fluctuations under a periodic order policy is obviously significantly shorter than for the two other policies, which is consistent with the qualitative results of symbolic time series analysis.

5. Consequences for production organization and planning

This section undertakes a deeper evaluation of the general performance of manufacturing systems under different order policies with respect to results from the previous sections. In addition, some implications will be discussed concerning general strategies that can be used to optimize networks of production and logistics.

5.1. Applicability of order policies

The preceding sections described the modeling, simulation, and analyses of one specific model of a network of production and logistics. To be able to implement the rather theoretical results into real-world systems, these have to be "translated" to more general systems. The following takes a deeper look at the different order policies analyzed in this study and points out their individual advantages and disadvantages.
5.1.1. Provision policy

Considering the time series from the model using the provision policy for the ordering of material, the long initial transients, which may last up to 10,000 simulation periods or even longer, are an important observation (see Figs. 2 and 3), as they indicate that after an initial perturbation of the production process the network needs a rather long relaxation time to get back to its equilibrium dynamics. Furthermore, this policy is characterized by relatively large inventory levels. In contrast to these disadvantageous features, it is however also found that the stock distributions are very robust with respect to fluctuations of the demand as well as variations of the different model parameters. However, this robustness comes at the cost of a large probability of the already-mentioned very high stock levels. Therefore, the findings clearly suggest that the provision policy is not suitable for products or production processes with a rather short product life cycle because of the rather long initial transients, which contribute to the high stock levels. In contrast, the provision policy may be suitable for products whose demand varies strongly with time. This is because of the generally high stock level. Altogether, the provision policy may be used for the ordering of materials even in situations or networks in which strong dynamics occur. But because it is a rather simple policy, this positive effect is supplemented by high inventory levels and, hence, high storage costs.

5.1.2. Order point policy

In the case of an order point policy, the behavior of the model resembles that under a provision policy at least in some parts of the time series. In particular, the existence of a rather long transient phase at the beginning of the time series is comparable (see Figs. 2
and 3). Therefore, the order point policy is also not well suited for products with a rather short product life cycle (the corresponding lifetime in a real-world problem depends on the specific time scales involved for product development, supply of commodities, and production) due to the already-mentioned reasons. However, in contrast to the provision policy, after the passing of the transient a high degree of regularity is found, which is manifested in a stable long-term periodicity of the stock levels. Moreover, as can be seen in Figs. 2–4, this policy yields the lowest stocks for those buffers that are equipped by external suppliers, while in contrast to this observation the other production lines may show larger inventory levels, which may in addition become very large in case of temporal variations of demand (see Figs. 2 and 3). Regarding all of these observations, it is evident that the order point policy is especially suitable for the long-term production of products with only weak variations in customer demand. In particular, the study reveals that under the considered conditions the production process is much more regular (in many cases even periodic, see Figs. 2 and 3) and, hence, more predictable than in the presence of the other order policies, which is beneficial for long-term planning of production. However, to generalize these observations, additional systematic consideration of other settings is required, which is beyond the scope of this paper.

5.1.3. Periodic order policy

In contrast to the provision and order point policies, the periodic order policy does not show a long transient phase. This result makes this policy suitable for the ordering of materials in the production of goods with short product life cycles because an accurate amount of material is ordered already at the beginning of the production, which leads to decreasing costs. Furthermore, the periodic order policy leads to a rather low stock level in all production lines. In addition, variations of customer demand do not increase stock levels. It was found that demand variations can even lead to a decrease of average buffer levels. The mentioned general features are qualitatively robust under variations of the main model parameters. All of the findings concerning the periodic order policy suggest that, in comparison to the other strategies examined in this work, this policy is the most appropriate when it comes to ordering. This result is mainly a consequence of the variability of the parameters that determine the order point as well as the amounts of material ordered. It must be noted, however, that maintaining the good performance of the periodic order policy requires short intervals of checking the available stocks and eventually ordering new material. From the point of view of the possibly resulting number of individual orders and the corresponding transportation processes as well as the required inspection of inventories on a regular basis, the overall costs for ordering of material can be significantly higher than for provision and order point policies; however, the storage costs may be lower. Whether or not there exists an optimal balance of both costs that requires lower overall expenses than the corresponding optima obtained for other order policies most probably depends on the specific situation and shall not be discussed further at this point.

5.2. General results

The planning and control of production and logistics networks is a challenging and complex process. On the one hand, this is caused by network-external influences such as dynamic customer behavior. On the other hand, the increasing complexity of the internal operational processes on both the strategic and operational level, the high importance of the information collection and preparation, and the fast and uncomplicated propagation of relevant data are developments that contribute as well. Based on the analyses of the generated simulation models, different general methods and strategies can be derived and thoroughly compared in regard to both organization and planning. It is the aim of future research work to detail these findings and implement them not only in simulations of the described network but also for the control of a real-world system to prove the suitability of the results. The following will discuss some of these possible approaches.

5.2.1. Decoupling of nodes

Recent analyses of different simulation models have revealed that a too-close coupling of the network nodes is a negative factor for the operation of a network of production and logistics [24]. This finding has been considered in the implementation of the simulation model in terms of short transportation times as well as direct delivery structures between suppliers and customers, which has, however, led to increasing dynamics of the logistic observables (in particular, the inventory levels) or even to a completely irregular system performance. As a possible counterstrategy, an uncoupling of the network nodes is suggested, which can be achieved by different approaches.

The general approach for uncoupling two systems is the integration of buffers that are arranged between the two affected systems. The implementation of such elements involves additional costs for storage systems as well as higher inventory costs. Nevertheless, some positive effects can be observed as well.

Realization of this approach in the situation studied in this work can only be achieved by increased expenditures because external, not internal, logistic operations are examined. Consequently, distribution logistics processes are the focus of interest. Distribution logistics provides various approaches for the uncoupling of different systems. A comparative analysis and selection of particular strategies has not yet been made up to this point because the effects of different distribution channels have not been explicitly considered in the presented research.

5.2.2. Synchronization of processes and process parameters

The analysis of the simulations underlines the general necessity of a synchronization of the relevant processes of all network participants. The negative effects of a lack of synchronicity in terms of deviating planning and control methods and nonadjusted process capacities and parameters, as well as an only-local and usually not sufficient information basis, have been observed in different simulations.

Regarding the background of the problem, a closer mutual cooperation and agreement is strongly recommended. Possible starting points for this are the formation of cooperations or alliances. In addition, a change of the institutional form of the involved enterprises – for example, in terms of joint ventures, by mergers, or in a reduced form also by franchising or the development of mutual relations within consortia – may significantly contribute to an improvement because a broader information basis is generated and common goals and visions are coordinated and communicated. In this context, the use of learning processes can also be considered as a possible approach to meet the described problem, which in general allows an improved mutual understanding of possibly different positions.

While the preceding recommendations have mainly concerned the organizational level, additional more technologically oriented approaches can be considered also to improve cooperation. For example, for an improvement of the common information basis, the network-spreading employment of radio frequency identification (RFID) technology is a promising concept for collecting real-time data. The automatized collection of different logistic as well as technical data can (if they are suitably analyzed and evaluated) crucially contribute to an exhaustion of the enormous optimization potentials. For the accurate definition and
observance of process cycles, the use of workflow management systems is recommended.

If a change of the institutional organization and/or a closer cooperation of the remaining network participants is not possible, the integration of specialized service providers can be a conceivable alternative. Here, in particular, the concept of fourth-party logistics [53] has to be mentioned. In this context, a main goal is the unification of existing service offers into an optimal package, whereby a maximum of cost lowering and efficiency in the entire logistic chain can be achieved.

5.2.3. Reduction of external dynamics

An element that can particularly affect the dynamics in networks of production and logistics is external market dynamics, which have a considerable influence on system performance. The potential of methods of planning and control to minimize the corresponding negative effects is, however, rather limited.

To be able to react to future customer demand in an adequate way, suitable forecasting methods are first required. Wrong or inadmissible prognoses can lead to serious consequences because either too much or too little material is ordered. Among other problems, this can cause higher stocks with rising costs for purchase and storage as well as a serious risk of production downtimes. Therefore, accurate and reliable methods are necessary for prediction of customer demand. Until now, corresponding approaches are mainly based on simple statistical methods such as weighted averaging of preceding values. Although these methods are well accepted and may be rather reliable in certain situations, suitable concepts for a quantification of the quality of demand forecasts are still missing. As a possible measure for an appropriate characterization of the theoretical prediction limit, entropies have been recently suggested [60].

Besides improvement of the forecast quality, there are further approaches that can be used to reduce the effects of external market dynamics. However, these concepts deal more with the strategic level than with the operational level. If possible, existing production capacities should be used more uniformly for the production of goods with temporally shifted customer demand. The attempt of opening new markets leads in a similar direction.

In the case of products for which a longer storage period (and corresponding amount of fixed capital) is uncertain, there is the possibility of constant production. During times of lower customer demand, products that are not immediately sold on the market are stocked, while during periods of high customer demand this stock can be used to satisfy the demand that cannot be filled through production capacities.

6. Conclusions

This paper has described that small-scale networks of production and logistics already show strong dynamics that can affect their performance. Based on the analyses of discrete-event models, general methods and strategies were evaluated for the management and control of networks of production and logistics that can help to minimize the economic effects of the identified dynamics. To make more accurate statements for the control of such systems, detailed investigations of more complex models are essential. These will be developed and studied with suitable (in particular, nonlinear) methods of time series analysis, such as those applied in this paper.

A conceptual framework has been presented based on nonlinear time series analysis that allows quantitative comparison of the behavior of production and logistics networks in a variety of situations. Symbolic time series analysis and recurrence quantification analysis yield a variety of measures that are, in principle, well suited for this purpose. However, as the symbolic encoding of the considered stock time series leads to an artificial behavior of some measures, the computation of nonlinear characteristics based on the RQA appears to be superior and of considerable value for a characterization of the performance of manufacturing networks. A combination of both approaches may offer a further improvement [20].

The methodological framework introduced in this paper is general enough to be systematically applied as a tool for performance testing and evaluation of different control strategies. In particular, it goes beyond recent studies in that the variety of different statistical parameters offered by RQA allows a detailed characterization of different aspects of dynamics such as complexity, regularity, and predictability. The range of possible applications is not restricted to theoretical models but also covers real-world production systems. A corresponding study will be presented in a subsequent publication. In this respect, a systematic performance evaluation of manufacturing networks by the proposed nonlinear methods (using extensive simulations) may help to improve such systems on both the strategic (planning) and operational level, offering additional insight into the potential dynamics in a variety of systems operation situations.

This paper was focused on one standardized setting that does not necessarily cover the variety of dynamics that can be shown by the network model. In particular, the results about the detailed performance of different order policies relate to this specific setting and may not necessarily be generalized. Consequently, it is planned to extend the investigations to (i) a systematic investigation of the model dynamics if different process parameters (especially operation and transportation times as well as lot sizes) are varied; (ii) comparable systems with a higher number of nodes; and (iii) other, more detailed, models of real-world networks of production and logistics. In the framework of the corresponding investigations, the results obtained from the simple theoretical models analyzed in this study will be further validated and modified wherever necessary.

Acknowledgments

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Appendix

Below are the relevant parameters of the simulation model and their values for the settings discussed in this paper:

- Time step of simulation: 1 h
- Transportation times: 1 h for all transports
- Operating (processing) times: 1 h for all production lines
- Working-on intervals: 1 h for all production lines
- Lot sizes: 1
- Initial inventory levels: 5 for all buffers
- Order volumes, q (only provision and order point policy): 8 for buffers equipped by external suppliers, otherwise 3; orders may be realized with a period of 6 time steps (hours)
- Order points, s (only order point and periodic order policy): 10
- Ordering intervals, r (only periodic order policy): 8 h for manufacturers, 24 h for external customers
- Amplitude of constant external demand: 3 (per ordering interval)
- Amplitude of external demand, A: 20
- Period of external demand, T: 90 h.
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