Impact of Market Dynamics on Performance and Internal Dynamics of Job-Shop Systems

Bernd Scholz-Reiter, Christian Toonen and Dennis Lappe

***Abstract*—**The importance of dynamics in production and logistics networks has increased steadily over the last years. This applies for internal and external dynamics alike as both often affect the system's performance.

In this article we study the impact of external dynamics on performance and internal dynamics of job-shop systems. For this purpose we develop and discuss a continuous model of a job-shop system and examine the feasibility of a load-oriented capacity design. Subsequently, we employ the developed model to study the impact of external fluctuations on the system's behavior and key performance measurements.

***Keywords*—**Continuous Model, Job-Shop System, Load-Oriented Design, Market Dynamics, Performance.

I. Introduction

NETWORKS of production and logistics incorporate interacting units. The multilateral interactions between these units (related by material and information flows) induce structural and dynamic complexity for the overall system [1], [2]. The dynamic behavior of the system is determined by internal and external factors. Whereas internal settings are subject to the system's design, production planning and control (PPC) [3], [4], external factors are mostly given by market dynamics, e.g. in terms of fluctuating quantities, changing order specifications and alternating due dates. Against this background particularly job-shop systems are affected by dynamics. On the one hand, job-shop systems feature strongly cross-linked material flows which comprise multiple dependences pushing the internal dynamics [5], [6]. On the other hand, companies applying job-shop systems often produce tailored products in low quantities for individual yet numerous customers. Therefore, these organizations are exceptionally influenced by general market trends and customer-driven changes of purchase orders.

The dynamics within a production system and its performance are closely connected [7]. Therefore, in order to improve the system's performance, an enhanced understanding of causes, interdependences and impacts regarding the dynamic behavior is required. This refers particularly to the complex interplay of internal and external dynamics associated with job-shop systems. Here, the understanding of the dynamic behavior and the influences of design, production planning and control can be supported by means of simulation [8]-[12]. This approach allows for a system to be modeled, simulated and analyzed to test and to assess alternative specifications and measures or to investigate general dependences [13].

Job-shop systems are mostly studied applying discrete-event simulations (DES). They allow a detailed reproduction and analysis of the real system [8], [9]. However, these advantages cause high modeling efforts while time scales under study are often limited. Considering the influences of external dynamics, a continuous modeling and simulation approach offers additional and partly complementary research possibilities despite the system's discrete characteristics [14].

In the following we introduce the characteristics of job-shop systems, examine the applicability of a continuous modeling approach and derive a continuous simulation model. Based on the developed model we investigate the feasibility of a load-oriented capacity design and discuss the impacts of deviations from these constellations. Finally, we examine the impact of different market dynamics on the system's internal dynamics and its performance.

II. Job-Shop Systems – Characteristics, Modeling and Simulation

A. Characteristics

Job-shop systems are organized by grouping machines of identical and similar machining function in designated production units called workshops, Fig. 1. These workshops are spatial and organizational units which constitute centers of concentrated knowledge and equipment [15]. Therefore, this type of organization offers a natural kind of flexibility which allows a fast adaption to changing production conditions, e.g. in cases of machine downtimes or changing machining requirements [16]. This inherent flexibility is particular beneficial for manufacturing heterogeneous production programs with often changing products. Linked to high product variability one often finds small production quantities which comprise small lot sizes and often include customer-specific products [17]. The multitude of products entails a high variability of production orders. Thus, the overall material flow formed by these production orders is often

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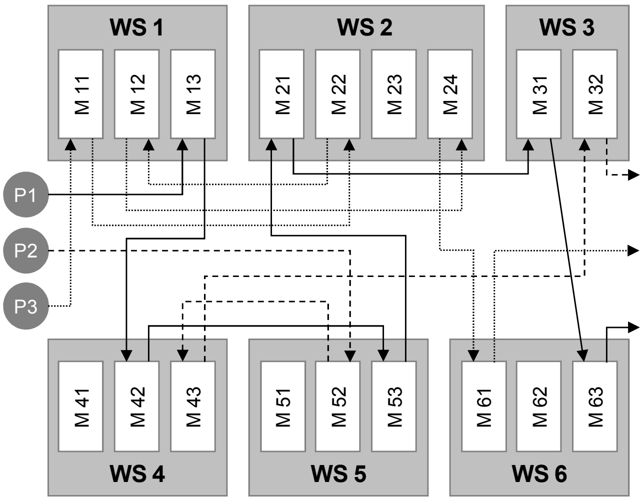
highly cross-linked, multi-directional and discontinuous, Fig. 1. These conditions, the re-entrant structures and the complex interplay and dependences of machining, transportation and handling steps foster the development of complex internal dynamics. Especially close to the upper capacity limit the production and logistics system tends to complex dynamics [5]. This is followed by unpredictable inventory evolutions, prolonged lead times and reduced utilization [6]. Thus, the system's overall performance is affected.



P – Product; WS – Workshop; M – Machine

Fig. 1 concept of a job-shop system [18]

The long-term conditions of the system's dynamics are given by the definition of structures and capacities, the short-term dynamics are mainly determined by order release and specific settings of PPC [13], [19], [20]. Order release triggers the order-related material flow thus inducing the system's dynamics. Transportation of incoming orders is mostly carried out by floor-born transport vehicles connecting material entry, machines within the workshops and material exit. Necessary machining steps and workshops an order has to address are usually specified by an order-specific work plan. This plan lists the succession of machining requirements as well as standard processing times.

Within a workshop an order is allocated to the available machines by specific rules, e.g. by considering lowest current inventory, set-up times and due dates. In case a machine is already processing an order, subsequent orders have to wait in an up-stream buffer. In case all transport vehicles are in operation after the order is machined another amount of waiting time occurs in a down-stream buffer. Thus, the stopover time of an order in each workshop is determined by the sum of waiting times and processing time. Once an order has been completed according to its work plan it exits the system through the material exit accounting for its throughput time.

The performance of a job-shop system is often linked to the achievement of specified values for inventory levels, throughput times, capacity utilization and adherences to delivery dates [21]. These are conflicting objectives: an improved capacity utilization often conditions increased inventory levels and prolonged lead times. Similarly, short and reliable throughput times often affect capacity utilization. At the same time, manufacturing companies and their customers traditionally strive for different goals: whereas a company often intends to achieve high capacity utilization, customers mostly call for short and reliable delivery times. Therefore, along with the increased power given to customers by globalized and multi-supplier markets, nowadays most companies focus on a customer-oriented achievement of these conflicting objectives. Here, functional dependences and typical curves support the positioning within the conflict of objectives according to a company's priorities [7], [22], [23].

The dynamics of a job-shop system are mostly related to its inventory evolutions. These are the outcome of initial inventories and incoming and outgoing orders. Here, complex internal and external dynamics condition highly volatile evolutions [24]. The quantification of inventory can be executed following two alternative possibilities. A simple way to measure inventory is counting waiting and currently machined orders within each workshop. However, this approach neglects different order sizes. Therefore, an improved coverage of inventory is given by the consideration of the estimated order-related machining times. These machining times are calculated by considering the standard processing times given within an order's work plan and its lot size. Accordingly, inventories are measured in units of time their evolutions being discrete in time and in value.

B. Modeling and Simulation

Due to the discrete characteristics of job-shop systems, e.g. regarding individual production orders and machining steps, modeling and simulation are often carried out applying discrete-event simulation (DES) [8]. DES is an exact method with high complexity as relevant objects are modeled individually [10], [25], [26]. An event characterizes changes in the system's state, e.g. triggered by steps of machining or transportation. These changes occur in discrete time steps and discrete values causing abrupt changes described by one or more variables [9], [27].

DES is mostly applied to examine operational and tactical questions on short time scales. Here, detailed results on future states of the system can be simulated and assessed by chosen criteria [28]-[30]. However, efforts of detailed modeling and simulation increase considerably with the system's complexity and time scales under study. Here, a continuous modeling and simulation approach offers complementary characteristics [14], [31]. Due to its reduced detail level the continuous approach causes less modeling efforts and allows studying more strategic matters on large time scales [25]. Opposed to DES the continuous simulation approach assumes a model's constant progress over time. The system's settings are modeled by a set of coupled differential equations which include time as a variable. Starting at a single point in time, the simulation of future states is carried out by calculating and solving the underlying differential equations. Characteristical within the modeling process is the consideration of feedback loops. These loops represent the interplay of the system's elements and variables. This allows identifying essential dependences and important factors for the dynamic behavior [28]. Therefore, continuous simulation is mostly applied to investigate nonlinear dependences and complex dynamics opposed to concentrating on single processes and elements within the system [32], [33].

Compared to DES, continuous models are approximations of the system under study. When modeling discrete systems they entail simplifications and assumptions causing a loss of details, e.g. by approximating discrete objects and discontinuous events by continuous flows established using average values [9]. As a consequence, discontinuous and irregular events like machine breakdowns or maintenance work have to be considered within the general settings. Accordingly, the analysis of single objects within the model is not feasible or requires special modifications.

Continuous simulation models are often called System Dynamics models with respect to the method developed by Jay W. Forrester to implement continuous models [34]. System Dynamics provides the possibility to model either qualitatively or quantitatively. Qualitative models allow the identification and the investigation of feedback loops. However, studying the impact of external dynamics on a job-shop system and calculating logistics key figures requires a quantitative model, also known as stock and flow model [35].

III. Simulation Model

In the following we describe the derived continuous simulation model. For this purpose we refer to its basic elements, the system's structure and its internal material flows. For implementation and simulation of the model we applied the software *Vensim* by Ventana Systems, Inc.

A. General Approach and Basic Elements

In order to design a continuous model the discrete characteristics of job-shop systems need to be simplified to suit continuous properties. This applies particularly for production orders which have to be approximated by a merged and averaged continuous flow. The necessary data for this approximation is given within the master production schedule. This schedule provides data about planned production quantities and products for a given period of time. This information, in combination with the product-related work plans, can be employed to derive a matrix of material flow. This matrix describes the average quantities of material exchange between order entry, order exit and particularly between the workshops of a job-shop system. The flows within the model are distributed in accordance to the average values within the matrix. The dimension of these flows is *parts per time* being a continuous value.

The derived model comprises elements of machining, buffering and transportation. In order to design any necessary configuration these elements can be combined in a generic way. Basic elements of the model are workshops which are created employing modules. Each module comprises a workshop and related up-stream and down-stream buffers, Fig. 2.

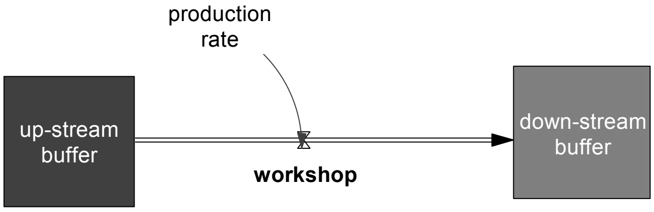


Fig. 2 module for a workshop

The up-stream buffer accumulates the incoming flow and directs it to the associated workshop. The workshop is represented by a valve which allows a certain amount of flow to pass limited by a production rate. The production rate reflects the overall capacity of the workshop. The down-stream buffer has the function to collect the throughput flow and to distribute it to following workshops and the order exit in accordance to the material flow matrix. In order to avoid internal dynamics we exclude rules for the allocation of incoming flows to machines within the workshops. As a result, the existence of machines within the model is of no consequence for the continuous model. Therefore, we restrict our simulation model to the detail level of workshops.

Between order release, workshops and order exit transportation is necessary. Comparable to the design of workshops, transportation times are approximated by valves. These valves are not limited in terms of through flow but act as delay element. Thus, an incoming flow is delayed for a certain amount of time representing the transportation time. The necessary transportation times are given by a transportation matrix. This matrix reflects the transport distances and therefore the structure of the underlying job-shop system, Fig. 3.

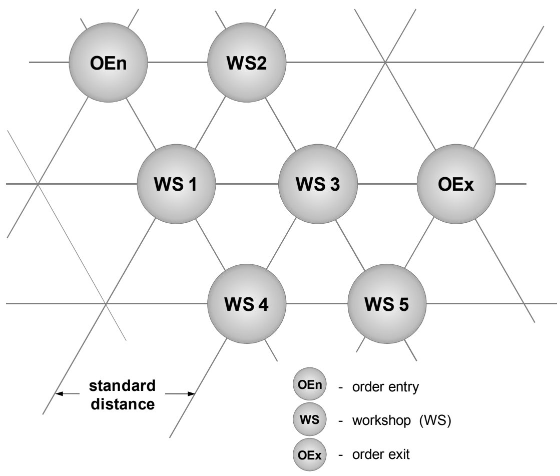


Fig. 3 grid of equilateral triangles with order entry, 5 workshops and order exit

For reasons of simplicity we consider the system's structure applying a simple grid of equilateral triangles. The workshops are placed on this grid minimizing overall transportation times of the exchanged material flows. The side length of the standard triangle of this grid corresponds to a standard distance and therefore a fixed transportation time.

B. Material Flow

The material flow into the system is triggered by order release within the order entry, Fig. 4. The developed model allows designing input flows of arbitrary mathematical function. From order entry the incoming flow is distributed to the workshops as given by the matrix of material flow. The flow intensity to each workshop is set by distribution ratios. The transportation from order entry to a workshop requires a certain amount of time as given by the transportation matrix. After transportation the material flow is gathered and forwarded by the up-stream buffer of the associated workshop. The production rate determines the amount of maximal flow-through. The rates of each workshop can be set individually, our programming guaranteeing non-negative inventories. After passing a workshop the material flow is either directed to the next workshop or forwarded to material exit. Due to the re-entrant structures a steadily decreasing amount of inventory remains within the overall system not reaching the order exit. Therefore, the simulation terminates once a specified amount of inventory has gathered within the exit.

The system's states throughout simulation are represented by inventory levels. This refers particularly to the inventory within the workshops and the inventory gathered within order exit. The related state variables are calculated using simple mathematical equations considering initial inventory, inflow and outflow of each element. In addition to inventory, performance of the overall system is measured by calculating capacity utilizations and total throughput time. The capacity utilization of each workshop is given by relating its times of operation to the overall throughput time. In case the production rate is not used maximally operation time and capacity utilization are reduced accordingly.

C. Load-Oriented Capacity Design

The capacity of each workshop and therefore the capacity of the overall job-shop system is given by the settings of all production rates. In order to avoid internal dynamics within the system, we design production rates and material relations being invariant in time. Furthermore, all flows within the system are treated equally excluding dynamics caused by priority rules (see above).

Following these conditions, the continuous modeling approach enables a load-oriented capacity design. This design creates the prerequisites for constant internal flows. Herein, the production rates of each workshop are fixed to equal exactly the workshop's inflow. These settings avoid inventory accumulations while maximizing capacity utilization once the system has reached a steady state.

The necessary values of the production rates are calculated by relating the flows for each workshop to the overall flow within the system. Thus, optimal capacity ratios for all concerned workshops are derived. Following this, the absolute values of the production rates are determined considering the material inflow.

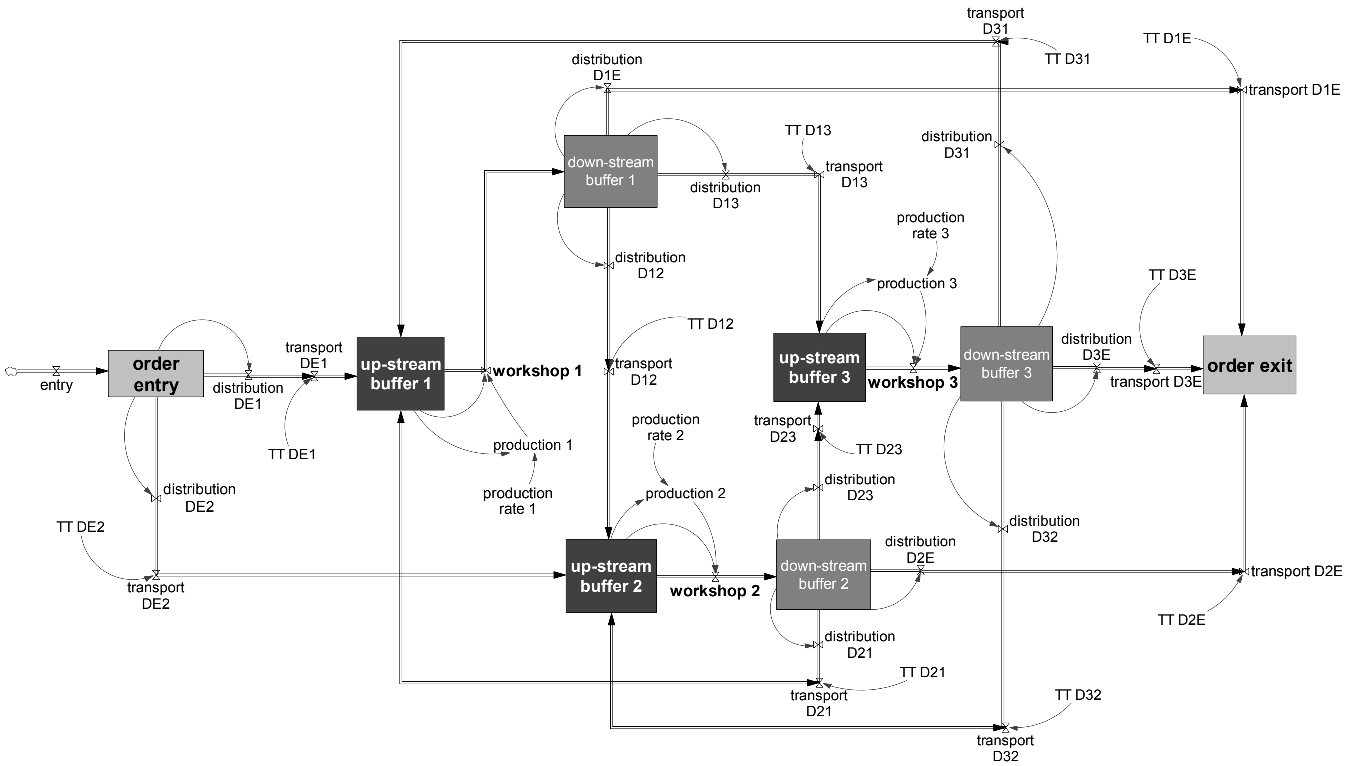


Fig. 4 simulation model with 3 workshops

Deviations from these optimal settings affect the overall performance of the system, e.g. an increased production rate in one workshop reduces its capacity utilization while entailing higher inventory levels in all subsequent workshops. Equally, a reduced capacity in a workshop establishes a bottleneck within the system which increases inventory and reduces capacity utilization in all subsequent workshops. Additionally, total throughput time increases.

IV. Impact of External Dynamics

Even though a load-oriented capacity design features advantages it requires a constant input flow. However, all kind of production systems are subject to external dynamics, especially in terms of changing due dates and fluctuating quantities. In the following we present the findings of a simulation study analyzing the impact of market dynamics on internal dynamics and logistics key figures of job-shop systems.

A. Simulation Study

In order to consider different system sizes we study job-shop systems with 3, 4 and 5 workshops (WS). The applied workshops provide production rates which approximate a load-oriented capacity design. We consider master production schedules and work plans which establish multilateral material flows between all workshops within the system. The input flow is modeled to exclude specified workshops, e.g. within the model with 3 workshops (3-WS-model) the order inflow supplies WS1 and WS2 but excludes WS3, Fig. 4. These conditions allow studying those inventory evolutions which are not directly influenced by the external dynamics but are the outcome of internal relations of the material flows.

The master production schedules comprise between 9 and 15 products each containing 2 up to 11 machining steps including re-entrant structures. In order to generate comparable results within all scenarios the absolute input is fixed with the same overall value. This value is distributed over the same amount of time determining the input flow and therefore the required production rates. The calculations of the system's states are carried out in fixed time steps which cover the system's overall dynamics. These dynamics are gathered by recording inventory evolutions of all workshops and the order exit. In addition, the capacity utilizations of all applied workshops and the overall throughput time are determined after simulation. The simulation ends when a specified amount of inventory has gathered within order exit.

B. Modeling and Impact of External Dynamics

In order to model simple external dynamics we superpose the constant input flow by sine functions, Fig. 5. Initially varying inflows are configured to represent the same total input over time with simultaneous variations of frequency and amplitude. In order to consider the influence of these two parameters, in Section C we present the impact of dynamics which are either modified in amplitude or in frequency.

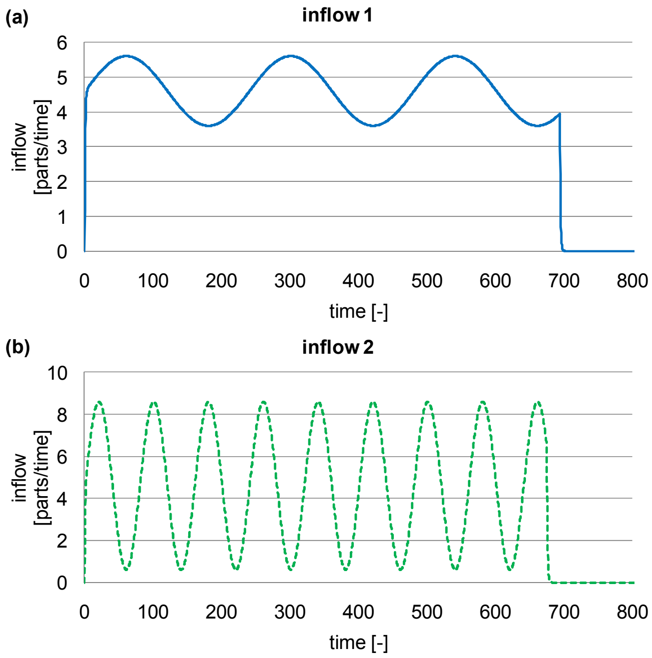


Fig. 5 (a) inflow 1 and (b) inflow 2 with equal total inflow but variations in amplitude and frequency

As the average inflow and the production rates within the models are harmonized, superposing the inflow with periodic dynamics represents a regular alternation between over- and underload. In case the up-stream buffers are supplied directly by order entry (this applies for WS1 and WS2 within the 3-WS-model) inventories adopt the impressed dynamics, Fig. 6. However, the inventory evolutions feature considerably enlarged average values and amplitudes.

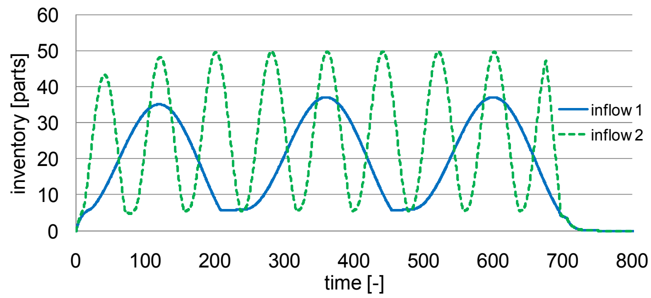


Fig. 6 inventory within WS2 for inflow 1 and inflow 2 (3 workshops)

These enlarged amplitudes are the outcome of the limited production rates on the one hand and the fluctuating input on the other hand. Once the inflow exceeds the maximal production rate of a workshop, inventory accumulates strongly. This applies similarly for being underloaded: once the inflow declines, inventories decrease quickly. Moreover, shortly after the inflow minimums, the workshops are not working at their maximal production rates. This reduces their capacity utilization and their throughputs for all subsequent workshops, in this case WS3, Fig. 7.

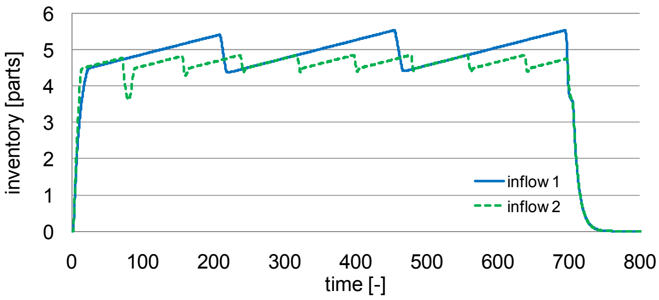


Fig. 7 inventory WS3 for inflow 1 and 2 (3 workshops)

WS3 receives its inflows as the flow-through of WS1 and WS2. As the production rate is slightly undersized the inventory increases temporarily. When WS1 and WS2 are temporarily not used at their maximal production rates, inventory and capacity utilization of WS3 are affected as well. However, the external dynamics are barely visible anymore. Accordingly, the average inventory level is notably smaller.

The simulations for the 4-WS- and the 5-WS-model deliver results comparable to the findings for inflow 1 and inflow 2 within the 3-WS-model. As inflow 2 features a higher amplitude than inflow 1 we observe higher mean inventories within the system than for inflow 1. The overall throughput times for different scenarios with the same overall input present about the same values. However, featuring the same overall input but varying amplitudes and frequencies we find that mean inventories and capacity utilizations do not feature definite trends. These circumstances are caused by mutual adjustments of frequency and amplitude discussed in the flowing section.

C. Influence of Amplitude and Frequency

So far we considered external dynamics with equal overall inputs. In order to analyze the influence of amplitude and frequency we generate external dynamics by fixing one of these parameters and varying the other.

Increasing the inflow's amplitude but keeping a constant frequency enlarges the deflections within the inventory evolutions of directly supplied workshops. As a consequence, mean inventories increase. Those workshops which are not directly supplied feature a constant inventory according to their production rates. The overall capacity utilization improves slightly. Increasing the inflow's frequency but fixing the amplitude, Fig. 8, we observe opposite trends: the inventory levels of all directly supplied workshops are smoothed by higher frequencies, Fig. 9. Although the external dynamics remain visible this behavior reduces the mean inventories.

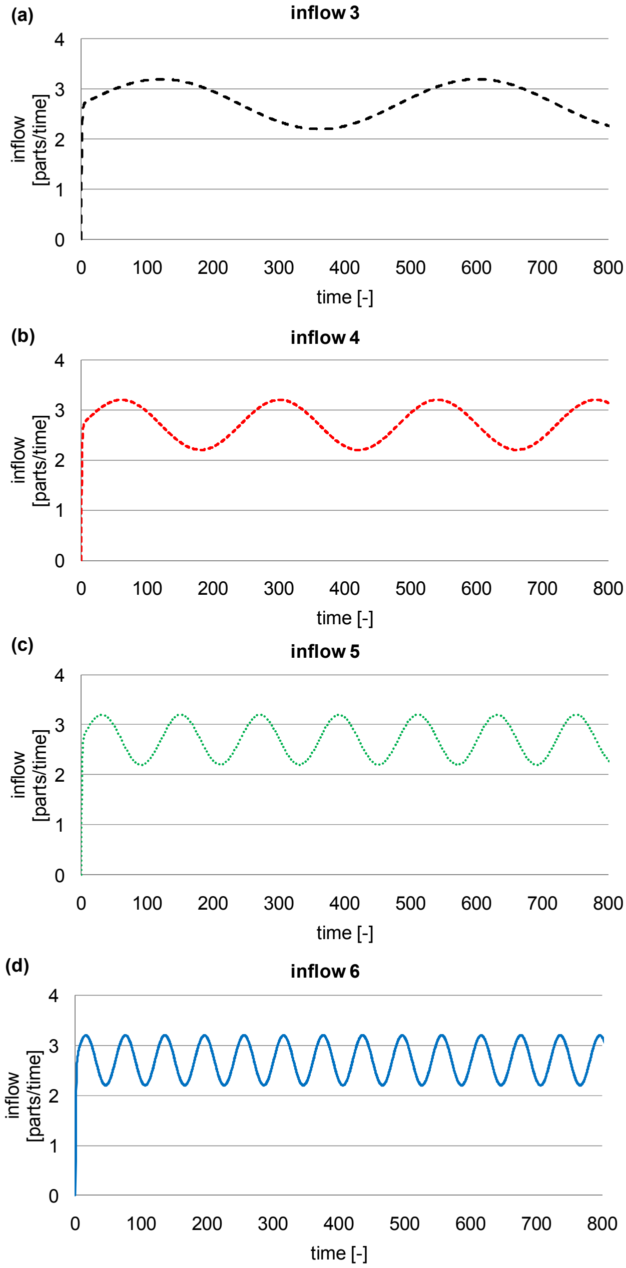


Fig. 8 (a)–(d) inflows 3-6 with constant amplitude but variations in frequency

Those workshops which are solely supplied by upstream workshops, again, feature nearly constant inventory levels although the temporal evolution differs influenced by the external dynamics, Fig. 10. Capacity utilizations and total throughput times remain nearly constant in these scenarios. Our results remain qualitatively unchanged when varying the number of workshops.

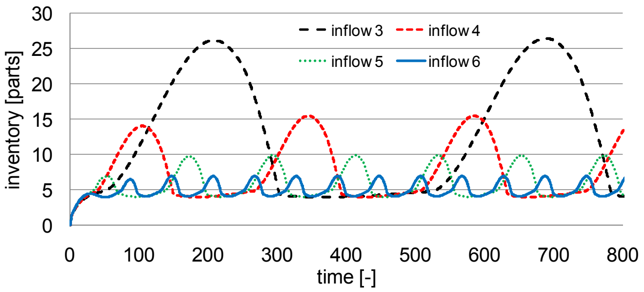


Fig. 9 inventory WS1 for inflow 3-6 (5 workshops)

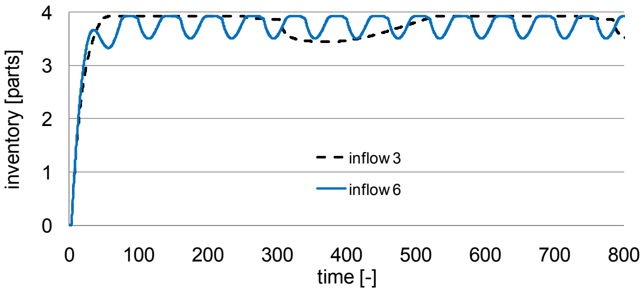


Fig. 10 inventory WS3 for inflow 3 and 6 (5 workshops)

V. Summary and Outlook

Market dynamics influence the internal dynamics and the performance of production systems. In order to analyze the impact of these dynamics simulations can be applied. Job-shop systems are usually modeled and simulated applying discrete-event simulation (DES). In this article we introduced the characteristics of job-shop systems and discussed the possibilities of the concept's coverage within a continuous model. Here, modeling discrete objects and events continuously requires simplifications involving a loss of details. This applies particularly for the consideration of objects and events within an averaged continuous flow. On the one hand, this reduces the resolution and the accuracy of the results, e.g. eliminating the possibility of analyzing specific orders in terms of lead times or adherences to delivery dates. On the other hand however, the continuous approach conditions reduced modeling efforts and provides additional analysis possibilities particular considering the system's long-term dynamics. Here, our model was applied to discuss a load-oriented capacity design and the impact of external dynamics.

The findings of the presented simulation study underline that market dynamics influence the system strongly. However, limited production rates filter the incoming dynamics and impede their spread. Yet, especially where workshops and market dynamics are directly linked, inventory evolutions adopt and enhance volatile inputs. In addition, we found that amplitudes and frequencies feature opposite impacts: inventories feature the lowest levels for small amplitudes but high frequencies. Capacity utilizations and total throughput times were found to vary only slightly within the considered scenarios.

So far we focused on capacities being invariant in time. However, changeable and reconfigurable manufacturing systems allow to be adjusted dynamically over time. Future research will focus on the impact of these changeable production systems. Here, the design of methods to control dynamic capacities as a powerful solution to cope with steadily increasing levels of market dynamics is of particular interest.

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