Job-Shop-Systems – Continuous Modeling and Impact of External Dynamics

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Abstract: Due to highly cross-linked material flows with various dependences the dynamics of job-shop-systems is often complex. In order to improve the understanding of these dynamics and to support the system's design, planning and control simulation is applied. Based on the discrete properties of job-shop-systems mostly discrete-event simulation (DES) is employed. However, DES entails rather high modeling efforts and is limited in its time frames. In this article we investigate the potentials of a continuous modeling approach and apply the derived model to study the impact of external market dynamics on the system's behavior and its logistics key figures.

Key-Words: Job-Shop-System, Continuous Modeling, External Dynamics

1 Introduction

The performance of a production system is closely connected to the system's dynamics. Therefore, an improved performance can be achieved by an enhanced understanding of causes, impacts and interdependences regarding the dynamic behavior of a system [1]. Generally, the dynamics are determined by the complex interplay of external input and the system's specification given by the design of production planning and control (PPC). These factors are subject to unexpected external and internal events, e.g. machine breakdowns, as well as intended adjustments by PPC and by design.

Both factors traditionally strive to minimize inventory levels and throughput times while maximizing capacity utilization and adherences to delivery dates [2]. However, particular job-shop-systems often feature complex dynamics which reduce the predictability of the system's behavior and affect performance [3]. Here, the understanding of the dynamic behavior and the influence and possibilities of design and PPC can be supported by means of simulations. These allow for a system to be modeled, simulated and analyzed to test and to assess alternative specifications and measures as well as to investigate general dependences [4].

Particular job-shop-systems are often studied applying discrete-event simulation (DES) as it allows a detailed reproduction and analysis of the real system [5]. However, these merits cause high modeling efforts while limiting the time scales under study. Here, a continuous modeling and simulation approach may offer additional and partly complementary research possibilities.

In the following we introduce the characteristics of job-shop-systems, discuss the potentials of a continuous modeling approach and derive a continuous simulation model. This model is applied to study the impact of external market dynamics considering logistics key figures of the system.

2 Job-Shop-Systems – Characteristics, Modeling and Simulation

2.1 Characteristics

Job-shop-systems are organized by grouping machines of identical and similar function in designated production units called workshops (Fig. 1). These workshops are spatial and organizational units which constitute centers of concentrated knowledge and equipment [6]. 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 [7].

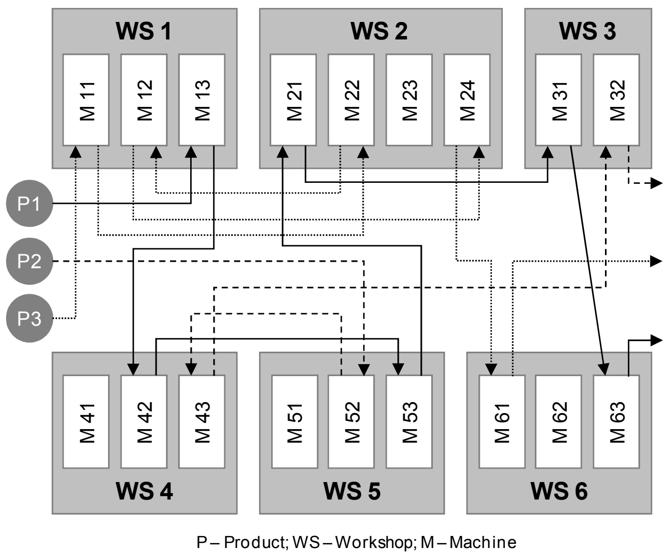

Fig. 1: Concept of a Job-Shop-System [8]

This inherent flexibility is particular beneficial for manufacturing heterogeneous production programs with often changing products. Linked to high product variability we often find small production quantities which comprise little batches and often include customer-specific products [9]. The multitude of products entails a high variability of production orders. Thus, the overall material flow formed by these production orders is often highly cross-linked, multi-directional and discontinuous. These conditions, the re-entrant structures and the complex interplay and dependences of machining, transportation and handling steps foster the development of complex dynamics. Especially close to the upper capacity limit the production and logistics system tends to complex dynamics and chaotic behavior [3]. This is followed by unpredictable inventory evolutions, prolonged lead times and reduced utilization. Thus, the system's overall performance is affected.

The material flow within the system is triggered by order release within PPC. Necessary machining steps and workshops an order has to address are usually given by an order-specific work plan. This work plan lists the succession of machining requirements as well as estimated processing times. Once an order is released by PPC it requests transportation and is conveyed to the first listed workshop. The transport is mostly carried out by floor-born transport vehicles connecting material entry, machines within the workshops and material exit.

Within a workshop an order is allocated to the available machines by specific rules, mostly by considering current inventory and set-up times. 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 the down-stream buffer. Thus, the stopover time in each workshop is determined by the sum of waiting and processing times. Once an order has been completed according to its work plan it exits the system through the material exit accounting for the total time through production.

The quantification of inventory within production can be executed by counting orders related to each workshop. However, this approach neglects different order sizes in terms of lot sizes and necessary machining times. Therefore, an improved coverage of inventory is given by the estimated, order-related machining time given by the work plan. The inventory evolution is a result of initial work in progress, incoming and outgoing orders. Here, job-shop-systems are often characterized by highly volatile evolutions which are discrete in time and value [10].

2.2 Modeling and Simulation

Due to the discrete characteristics of job-shop-systems, e.g. regarding discrete orders, machines and transport vehicles, a discontinuous material flow and inventory evolutions which are discrete in time and value, modeling and simulation are often carried out applying discrete-event simulation [4,5]. Here, every machining or transportation step is an event. Changes of observed variables occur in discrete time steps and discrete values causing abrupt changes of the system's state [11,12].

DES is mostly applied to investigate 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 [13,14,15]. However, the detailed modeling and simulation causes relatively high efforts and limits the range of possible time scales [5]. Here, a continuous modeling and simulation approach offers complementary characteristics.

Opposed to DES the continuous modeling approach is mostly applied to study strategic matters on large time scales. Generally the whole system and its dynamics are under study opposed to single processes [16]. Thus, essential dependences and important factors can be identified [13]. Characteristical is the consideration of feedback loops which represent the interplay of the system's elements and variables. This is particular beneficial for the modeling of material flows caused by re-entrant structures within job-shop-systems. However, compared to DES, continuous modeling entails simplifications and assumptions, causing a loss of details, e.g. by approximating discrete objects and discontinuous events by continuous flows established using average values [12]. As a consequence, discontinuous and rare events like machine breakdowns or maintenance work have to be considered within the general production settings.

Continuous simulation models are often called System Dynamics models with respect to the method developed by Jay W. Forrester to implement continuous models [17]. System Dynamics provides the possibility to model either qualitatively or quantitatively. Qualitative models allow the identification and the investigation of feedback loops. However, the study of the impact of external dynamics on a job-shop-system requires quantitative models, also called stock and flow models [18].

3 Continuous Simulation Model

In the following we describe the derived continuous simulation model of a job-shop-system. The implementation and simulation is executed within the software Vensim.

3.1 Basic Elements

In order to create a continuous model, discrete characteristics of job-shop-systems have to be simplified to suit continuous requirements. This applies particularly for production orders, which are integrated to form a continuous workflow. This flow is created by data generated analyzing the production program for a given period of time. Within the production program products and related quantities are given. This data, in combination with the product-related work plans, can be employed to establish a material flow matrix, which describes the quantities and frequencies of material exchange between order entry, order exit and the workshops of a system. Accordingly, the average input and output flows of each entity can be calculated.

The model comprises machining and transportation elements which can be combined in a generic way to set up any job-shop-system's configuration. Basic elements are workshops which are modeled employing modules. Similar to a DES-model each module comprises a workshop, a related up-stream and a down-stream buffer (Fig. 2). However, whereas DES allows modeling machines, the continuous approach is restricted to the detail level of workshops.

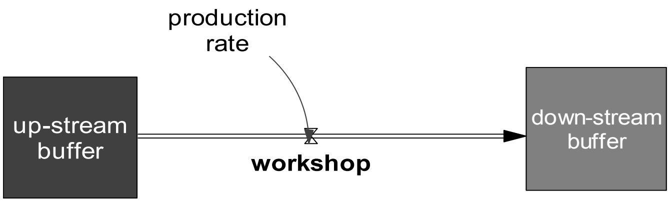

Fig. 2: Workshop module

The up-stream buffer accumulates the incoming flow and directs it to the workshop. The workshop is represented by a valve which allows a certain amount of flow to pass limited by a production rate. The down-stream buffer has the function to collect the throughput flow and to distribute it to following workshops and the order exit accordingly to the calculated material flow matrix.

Comparable to the workshops the transport is approximated by valves. These valves are not limited in terms of through flow but act as delay elements which cause an incoming flow to leave with a certain time delay representing the transportation time. The related transportation times are given by a matrix reflecting the system's structure. The structure and therefore the distances between the workshops are given by a simple grid of equilateral triangles on which the workshops are placed according to their material exchange [19]. The side length of the basis triangle corresponds to a fixed transportation time.

3.2 Simulation model

In order to represent different system sizes a job-shop-system containing 3, 4 and 5 workshops (WS) was modeled. Here, we took production programs and work plans as a basis which considers all possible material flow relations. However, in order to investigate the impact of external dynamics on the inventory evolution within the job-shop-system we modified the production program to establish one workshop to be excluded from a direct supply by order entry.

Fig. 3 shows the 3-WS-model. In this configuration the production program is designed to supply WS1 and WS2 by the order entry but to exclude WS3. The production

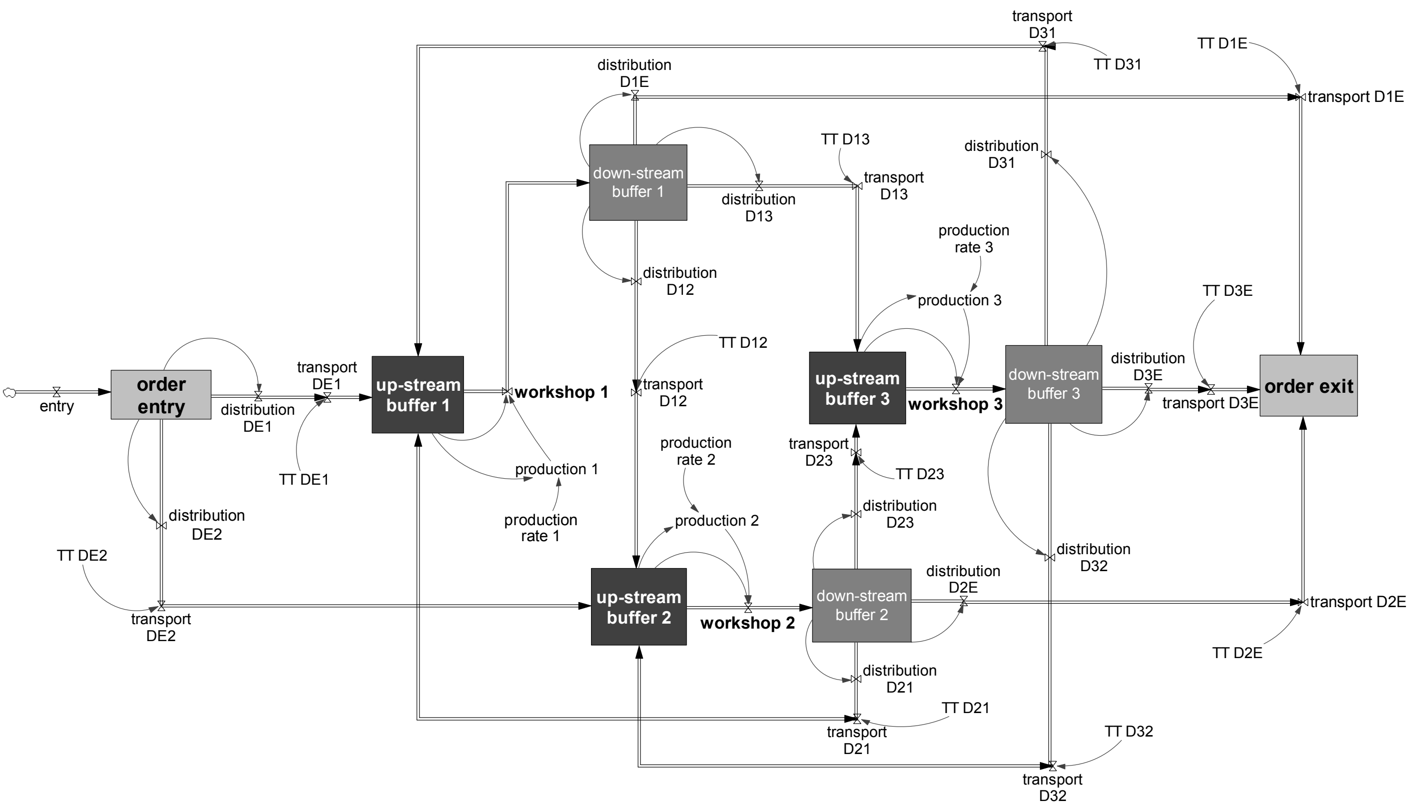

Fig. 3: Simulation model with 3 workshops

plan comprises nine exemplary products with a varying amount of machining steps. Additionally, re-entrant structures are considered allowing the multiple and repeated usage of the same workshop.

The system's states are represented by inventory evolutions, particular the inventory within the up-stream buffers and the outflow of inventory through the order exit. The related state variables are calculated using simple mathematical equations considering work in progress, inflow and outflow of each element. The production rates of each workshop are fixed uniquely considering the workshop's inflow. The programming guarantees zero or positive inventory allowing incoming flows to pass restricted only by maximum production rate.

4 Impact of External Dynamics

In the following the findings of a small simulation study analyzing the impact of market dynamics on logistics key figures are presented.

4.1 External Dynamics

All kind of production systems are subject to changing customer requirements and fluctuating quantities. This applies particularly for job-shop-systems and their heterogeneous and often changing production programs. A simple way of imitating these kinds of external dynamics is to superpose a constant input flow by various functions. Here, we defined rectangular-, sine- and triangle-shaped functions with varying frequencies and amplitudes. All inflow functions were configured to represent the same total input over time. Fig. 4 shows two alternative inflow functions generated using a sine function. However, at a defined point of time no more orders are dispatched by the order entry.

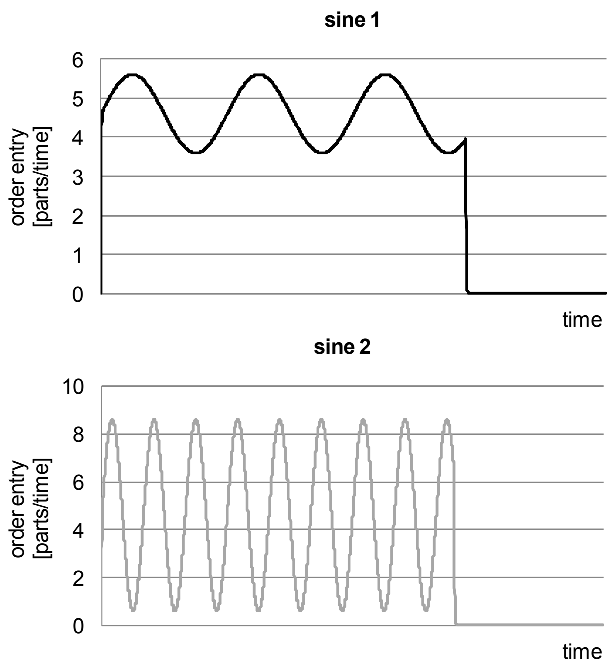

Fig. 4: Order entry inflow based on sine function

The capacities of the workshops were designed on basis of a load analysis guaranteeing production rates and ratios roughly appropriate for the inflow into each workshop. Here, the average inflow particularly regarding the order inflow corresponds to the production rate of each workshop. Thus, the superposition of a sine function represents a periodic alternation between over- and underload for the workshop.

4.2 Impact

Within the 3-WS-model the up-stream buffers of workshop 1 and 2 are supplied directly by the order entry. Accordingly, the related inventories adopt the impressed dynamics in frequency and amplitude after a small time delay caused by transportation times, fig. 5. Although the inflow alternations are quite small, inventory accumulates strongly over time resulting in high values. However, this relation applies as well for the underload entailing quickly decreasing inventory values. In addition to being supplied, both workshops feature a constant outflow of material given by their production rates. This outflow is particular visible once the inflow has stopped. Here sine 2 features a higher frequency and a higher amplitude than sine 1 resulting in a higher average inventory.

Though the production rate of workshop 1 does not suffice the inflow perfectly, which is the reason for a steady rising average level of inventory, within the sine minimums workshop 1 is not working at its maximum production rate.

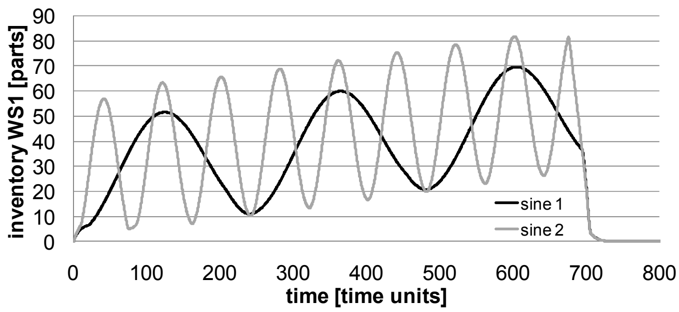

Fig. 5: Inventory up-stream buffer workshop 1

Workshop 3 receives its inflows created by workshop 1 and workshop 2. Although inventory increases slowly over time due to an undersized production rate, the applied sine function is barely visible anymore, fig. 6. Accordingly, the inventory level is generally smaller. However, as workshops 1 and 2 are not used to capacity within the sine minimums the inventory of workshop 3 decreases temporarily as well. Capacity utilizations and total throughput times were found to be nearly equal for sine 1 and sine 2.

The simulations for the 4-WS- and the 5-WS-model as well as for the rectangular- and the triangle-shaped inflows delivered results qualitatively comparable to the findings for the sine function within the 3-WS-model.

However, in additional experiments we found out that increased amplitudes cause a rise of average inventory. In contrast these results also show that higher frequencies support reduced and smoothed inventories.

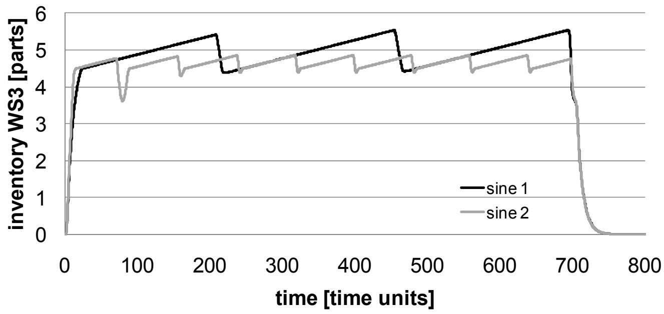

Fig. 6: Inventory up-stream buffer workshop 3

5 Conclusion and Outlook

Job-shop-systems are usually modeled and simulated applying discrete-event simulation (DES). Here, continuous modeling and simulation can complement the characteristics of 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. Despite its discrete characteristics a continuous modeling is feasible. However, modeling discrete objects and events continuously requires various simplifications and involves a loss of details. This applies particularly for the consideration of objects and events within a continuous flow. Here, the analysis of specific orders in terms of lead times or adherences to delivery dates is not possible anymore. Therefore, reduced modeling efforts, savings of time and additional results are gained by a reduced resolution and increased inaccuracy of results.

The derived continuous simulation model was applied to investigate the question to which extend external dynamics spreads through the system and influences its dynamics. The simulation study carried out underlines that market dynamics influences the system strongly especially regarding its inventory evolution in buffers where market inflow and system encounter. However, within a system designed on a load-oriented basis the spread of dynamics is filtered by limited production rates and fixed settings. Here, future investigations will focus on internally-driven dynamics, e.g. caused by intern processing rules.

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