Modelling and Control of Production Systems based on Nonlinear Dynamics Theory

B. Scholz-Reiter (2), M. Freitag, A. Schmieder
Department of Planning and Control of Production Systems, University of Bremen, Bremen, Germany

Abstract
Today's highly dynamic market with its rapid changing demand requires highly dynamic order processing in very flexible production systems. Most conventional production planning and control methods do not support such fast-moving activities. A dynamical approach is introduced for modelling and control of production systems. It was developed from concepts of the Nonlinear Dynamics Theory. Manufacturing processes as well as planning and control mechanisms are seen as one unit toward the establishment of a dynamical system. The dynamical approach includes an analysis of the dynamic behaviour of the production system as well as the control of the manufacturing process by a continuous adjustment because of changes or disturbances in the environment or in the production system itself.

Keywords:
Production, Control, Nonlinear Dynamics

1 INTRODUCTION

The development of Nonlinear Dynamics Theory and its applications in different fields enables us to understand and describe the dynamics of complex production systems where linear approaches fail or are too far from reality [1]. But complex dynamic behaviour can occur even in relatively simple production systems. Beaumariage and Kempf have shown the sensitive dependence of throughput times on the initial conditions and scheduling rules in a re-entrant production system model [2]. The origin of this unstable behaviour is not obvious. Beaumariage and Kempf suggest chaotic dynamics as being the reason.

To understand such complex dynamic behaviour of a production system, an intrinsic deterministic model is necessary, into which stochastic influences can be incorporated later on. Bartholdi, Bunimovich and Eisenstein have shown, that deterministic models can describe the dynamics of production systems appropriately. They described a sewing production line whose dynamic behaviour was exclusively driven by deterministic rules [3][4]. Understanding the production dynamics is therefore the motivation for modelling and control of production systems using Nonlinear Dynamics Theory.

Classical production planning and control systems (PPC systems) are based on concepts that do not consider the production system as a dynamical[1] system. Usually, heuristic approaches are preferred in order to simulate the production process and its scheduling and control. But optimisation methods do not provide the controller with good results if there are some changes during the optimisation period [5][6]. In the context of today's highly dynamic market with its rapid changes in demand, modern PPC systems have to deal increasingly with flexibility and variety.

This paper presents a dynamical approach for modelling and control of production systems based on Nonlinear Dynamics Theory, which incorporates the modelling of the dynamical aspects of the production systems in interaction with the control system that includes the functional aspects of PPC.

2 PRODUCTION MODELS AND PPC CONCEPTS

The usual models of production systems are derived from classical optimisation tasks studied in Operations Research [7]. The model for the production system itself therefore consists of different optimisation problems. There is no interaction of these particular theories. This could be developed in a meta-theory, but in general, the results will be hard to interpret [8].

Known concepts for production planning and control are normally founded on models for parts of the overall PPC job that solve local problems like the job shop scheduling [8]. Such optimisation models – solved by exact algorithms or heuristic approaches – are often not satisfying even at a low level of complexity [9].

Nevertheless, numerous PPC systems are based on these PPC concepts. Such a PPC system is designed to find optimal solutions for specific PPC problems. The most important optimisation goals are total costs, throughput time, capacity utilization, inventory costs and delivery reliability. Thereby, strategies for different objectives can lead to contrary results, e.g. maximal capacity utilization and minimal throughput times.

Most recent PPC systems work in line with the successive planning concept consisting of successive planning steps. It is widely used but also criticised because it lacks the interaction between the planning steps [8]. Several approaches try to overcome the difficulties resulting from this planning and control scheme [8][10]. They deal with local rules instead of global planning, event-oriented planning instead of planning periods or individual PPC modules in the context of decentralisation of control [10]. But they extend the possibilities of traditional PPC systems towards faster adaptation to changes in the environment of a production system.

[1] The use of "dynamical" rather than the simple adjective "dynamic" has become conventional in the Nonlinear Dynamics community.

3 THE DYNAMICAL APPROACH

The Nonlinear Dynamics Theory provides tools for the modelling of the dynamical aspects of a system and permits a continuous control of the dynamic behaviour during its operation. The dynamical approach consists of the modelling of the production system by means of its functional structure and its dynamical control via adjustment of the system parameters.

To apply concepts of Nonlinear Dynamics Theory, a production system is considered to be a dynamical system. Such a system has a set of parameters and system variables. The behaviour of the production system as a whole follows its intrinsic dynamics, which is influenced by the system parameters. As a result of the dynamics, the system variables change over time. [11]

The system variables span the state space of the system. The temporal evolution of the system state is represented by curves in this state space, the so-called trajectories which, under certain conditions, run towards an attractor. An examination of the geometrical structures of the attractor can provide information about the systems behaviour and also provides possibilities for control of the system [12].

It is possible to construct a qualitative equivalent to the state space of a system by measuring only few system variables that span a sub-space of the entire state space [13]. This sub-space can reveal the dynamics of the entire production system. The measured variables in a production systems are related to the work in the system like buffer levels or work-in-process (WIP) [5][6].

The state of the production system at any point in time is defined by a point on the trajectory in the state space. So it is possible to influence and control the state and the evolution of a production system by manipulation of the system trajectory. For this, several methods for the control of dynamical systems have been developed [12].

A dynamical system can be controlled either by forcing the system variables on defined trajectories or by variation of the system parameters. The usual method in PPC is the control of variables such inventory levels or work-in-process. But the idea behind the dynamical approach is the control of the intrinsic dynamics of a production system. This can be done by control of the system parameters which are considered to be flexible and capable of being influenced. Because of the high number of different parameters of a production system, they have to combined into functional groups that enable the system to work. The following functional groups are defined:

- the structure
- the capacity
- the operational rules
- the order release
- the queuing policies

These functional groups generate the dynamics of a production system and enable and influence the product flow through the system. They are at first a framework for modelling the production system and provide finally possibilities to control the production process by a controller or by the system itself. The latter case is a step towards self-control, which is a fundamental idea in the dynamical approach.

The idea of control put forward in this paper is the adjustment of these functional groups to meet the current requirements on the production system.

4 THE FUNCTIONAL GROUPS

4.1 The structure

The functional group “structure” contains information about the number and arrangement of work stations, machines, buffers or storages necessary to describe the manufacturing process sufficiently. The hierarchy of structural information allows a more or less detailed description depending on the modelling aims.

The structure also contains information about the product flow. It shows how different types of products can be put through a system. This becomes relevant, for instance, in parallel manufacturing facilities where it is possible to do the same job at different machines. The structure of the product flow is determined by the layout of the shop floors and by the process plans of every product in the production program. In a typical job shop production system, one finds a complex situation with a number of machines arranged according to their functions, e.g. turning, milling, drilling etc. Therefore, the product flow contains convergences, division and feedback loops.

The structure of the product flow is considered as a function of the structure and state of the production system. Changes in the structure, e.g. caused by machine replacements, immediately influence the structure of the product flow and system state due to the dynamic interactions.

4.2 The capacity

The capacity of a production system includes three important aspects: the capacity of space, the capacity of time and the capacity of manufacturing. The capacity of space describes the physical space to store and manufacture raw material, sub-assemblies and final products. Capacity of time means the working time in a day or week. The capacity of manufacturing contains the volume of production, product variety, quality measures and other parameters depending on machine parameters and structure.

Capacity is usually considered as a fixed parameter (or a set of parameters) in production systems characterized by upper and lower limits. In a number of models there are no capacity limitations.

In the dynamical approach, all three capacities are considered as variables that can be continuously modified. The flexible handling of the capacity of time (overtime work, part-time work) is a common procedure to balance costs and demand. The capacity of manufacturing is usually variable because the processes affecting this capacity change over time. An example for a large scale change is a growing product variety that causes additional setup processes at the machines. This increases the throughput times and so decreases the capacity to manufacture these products. Examples of small scale changes to the capacity of manufacturing are machine breakdowns or missing tools, late deliveries of parts or rush orders.

The interesting point within the dynamical approach is the assumption of a flexible capacity of space. So the role of storages and buffers could move from a passive box with fixed upper and lower limits to an active element, which can be controlled depending on the system state.

4.3 The operational rules

If demand exists and manufacturing orders are waiting to be released and processed, the operational rules generate the dynamics of a production system. Such rules are generally simple handling processes but need to be defined in detail for modelling and control purposes. An example of an operational rule is: what happens in a machine if the input buffer is empty or if the output buffer is full and how does this effect the adjacent machines and buffers [14].

There are some investigations that identify and eliminate such constraints in a production system. In the majority of cases, the product flow and the position of the constraint are considered to be constant and static. This assumption is appropriate for a flow shop production system with a constant demand and a constant product mix. But for a job shop, changing demand and customer-specific products are typical. In this case, the product flow and therefore the position of constraints vary over time.

The dynamical approach suggests a dynamic adjustment of the operational rules on the current situation in the production system. An example is given in the last section of this paper.

4.4 The order release

In conventional PPC systems, the production orders are released after the throughput time scheduling, the capacity planning and the order sequencing. Order sequence and release dates are more or less fixed. Such a production schedule assumes constant throughput times and capacity availabilities during the entire planning period. But the fixed production schedule becomes void, if rush orders must be released or resources fail.

The dynamical approach suggests a dynamic order release depending on both the incoming orders and the actual situation on the shop floor.

4.5 The queuing policies

Queuing policies are rules that determine the withdrawal of material from buffer to manufacture on a machine. A well-known and widely used queuing rule is “first in - first out”. Thereby, the processing sequence of the orders remains constant. Dynamic queuing rules like “least average static slack” or “least average dynamic slack” cause withdrawal depending on the stage of processing and due-date. But they do not take into account the situation at the work stations.

The dynamical approach allows the choice between different queuing rules. For the control of the order flow under quickly changing conditions, the dependence on the system state will play an important role.

5 THE NONLINEAR DYNAMICS OF THE PRODUCT FLOW IN A PRODUCTION SYSTEM

The following section demonstrates the nonlinear dynamics of a production system and proposes possibilities to regulate the WIP levels via nonlinear control mechanisms. The goal is to control the production system via its system state by means of parameter changes in the operational rules.

The operational rules are considered to be flexible and influencable by a controller. All other functional groups are kept constant. An elementary production system with two work stations as shown in figure 1 will be considered. This could be a part of a more complex production system where only the product flow between two work stations is considered.

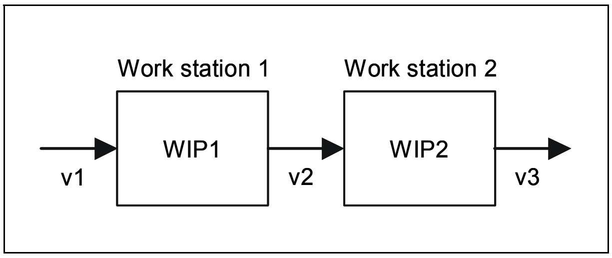

Figure 1: Flow model consisting of two work stations with work-in-process WIP and product flow velocity v.

The structure of the product flow is linear with one input and one output channel assigned to each work station. The current work-in-process of every work station is represented by the variable WIP. The product flow into and out of the work station is represented by the product flow velocities v, which can be interpreted as work per time unit.

Operational rules support the regulation of the product inflow depending on the work-in-process at the respective work station. That means, the higher the WIP level in the work station, the lower the product inflow and vice versa.

The work stations are coupled via the product flow velocity v2. A coupling parameter X is responsible for a tight or loose coupling of the work stations. The dynamic behaviour of this coupled system depends thereby sensitively on the coupling parameter X.

Lower values of X lead to a constant work-in-process. Thereby, the WIP level depends on the value of X. At a certain value of X, the work-in-process begins to oscillate between a low and a high level. Hereby, the minimum and the maximum WIP level depend on the value of X again. At a further certain value of X, the work-in-process oscillates between four different levels. Finally, larger values of X lead to unpredictable WIP levels.

This sensitive dependence of the WIP levels on the intensity of the coupling of WIP1 and WIP2 is shown in figures 2 and 3. These two typical bifurcation scenarios visualise the different qualities of dynamic behaviour depending on coupling parameter X. Bifurcations and deterministic chaos occur at large values of X, whereas lower values lead to a stabilisation of the WIP levels.

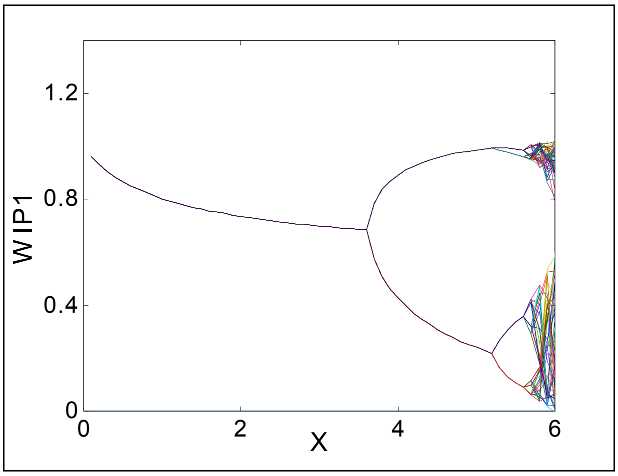

Figure 2: WIP level of work station 1 depending on the coupling parameter X.

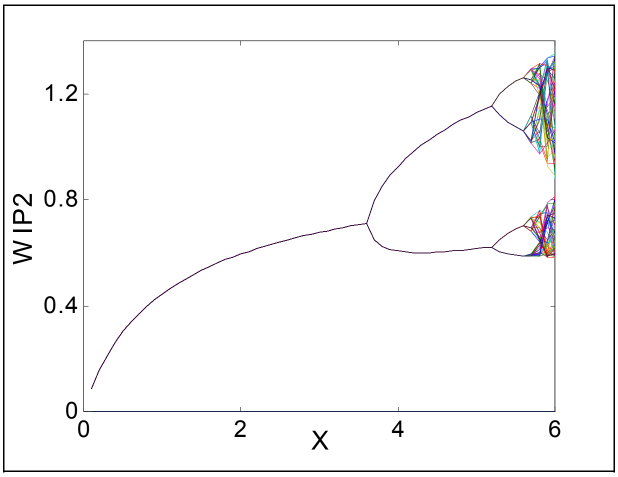

Figure 3: WIP level of work station 2 depending on the coupling parameter X.

The coupling parameter X can be used as a control parameter that permits the controller to operate the system in a stabilized mode or in a multimode. The multimode operation supports the adjustment of the WIP levels in a wide range because, due to bifurcations, WIP levels within an allowed range can always be reached. So it is possible to keep the work-in-process on a desired level.

A point of further discussion will be the interpretation of the parameter X regarding capacity control. This approach allows the exchange of available capacity between different work stations. This will be possible within a strict implementation of the dynamical approach, taking into consideration all five functional groups described in section 4.

A continuous control of the production process via its system state will be possible by simultaneous adjustment of all five functional groups. In this case, the application of Nonlinear Dynamics control methods could be possible, if explicit deterministic chaos occur.

But even now one can say, that nonlinear control mechanisms are useful for a rapid adjustment of the work-in-process and a quick adaptation of the production system on changes and disturbances in the environment or in the production system itself.

6 SUMMARY

Nonlinear Dynamics Theory enables an understanding and description of the complex dynamics of production systems. It provides possibilities for the control of production processes towards an agile operations management.

Taking up this, a dynamical approach for modelling and control of production systems was introduced that was developed using concepts of Nonlinear Dynamics Theory and PPC research. Manufacturing processes and PPC mechanisms are considered to be a unity that build a dynamical system in terms of Nonlinear Dynamics Theory.

The parameters of a production system, which influence the dynamics of the manufacturing process, have been combined into functional groups that enable the system to work. These functional groups are considered to be flexible and influencable by a controller. The possibilities of the dynamical approach have been shown for every functional group.

A simple model of a production system was discussed in the last section, demonstrating the function of nonlinear operational rules, which enable multimode operation for an adjustment of the work-in-process in the production system.

7 ACKNOWLEDGEMENT

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