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Stability Analysis of a Control-Theoretic Work System Model

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Abstract

Cyber-Physical Production Systems (CPPS), with their features such as distributed organization, autonomous control, real-time capability, and intelligent data processing, provide new production planning and control (PPC) capabilities. These possibilities are decisive in a market environment with characterised by smaller batch sizes, a large number of variants and shorter delivery times. However, it is necessary to have early-warning markers to take any measures.
In this paper, we deal with a particular control-theoretic model that is capable of simulating a work system, e.g.; a production machine. In particular, the model is able to predict the production duration of all incoming orders and, thus, serves the purpose of improving adherence to schedule of an arbitrary production environment. This paper aims to establish an appropriate stability analysis concept for this specific model. As it turns out, due to the nonlinearity of the model, we want to introduce a mathematically more challenging stability notion, the so-called *input-to-state stability*.

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Keywords: production planning; modelling; stability

1. Introduction

Manufacturing companies are currently exposed to a turbulent economic environment. Globalisation, the aggravation of product life cycles and the penetration of new technologies are just a few of the mega trends that manufacturing companies must face in order to be competitive [1, 2]. The customer expects an extensive product portfolio with individual characteristics with simultaneously short delivery times and a high level of punctuality [3]. This increases the demands on the production systems. In addition to technical product quality, logistical quality is also becoming an increasingly important criterion for a company's competitiveness [4]. As a result of the diversity of variants and the high pressure to innovate, companies are increasingly concentrating on their core competences and reducing their vertical range of manufacture [5].
Increasingly networked value creation makes modern supply chains vulnerable to disruptive events, and companies have a great need to identify unplanned events early and initiate immediate responses. Event-oriented systems fulfil the requirement of high reactivity to unplanned events, since they can recognise and respond to certain events or event constellations [6]. These disturbances cannot all be ruled out in a complex product. Simulation and prediction software systems are unlikely to predict the disturbance, but the impact of negative events can be illustrated.

Since the 1990s, with the advent of user-friendly simulation software and growing computational capacities, both model-based and, in particular, control-theoretic approaches to production planning and control (PPC) have gained increasing potential [7, 8]. A crucial step in this development was the contribution of Dirk Petermann [9]. Petermann and other authors who established a control-theoretic concept in order to model and simulate the transient behaviour of arbitrary work systems, e.g. production machines [10, 11, 12]. A respectable work system model should be able to react to certain events such as rush orders or capacity disturbances in real-time. Above all, the model is supposed to draw up an estimate for the production duration of any incoming order, so that simulating the model may help in keeping to schedule.

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2. Background - control-theoretic approaches

The origin of Petermann's approach is the so-called *funnel formula* [9, 13]. This states that, assuming the production follows a *first come first served* scheme, the mean throughput time (MTT) can be deduced from the quotient of the work system's mean stock (MS) and its mean performance (MP), i.e.,

$$MTT = \frac{MS}{MP}. \tag{1}$$

Based on the funnel formula and control technology approaches, Petermann has created a continuous model of the production process based on the continuous element [9] and the operating characteristic. Through the classical application of control theory, he realises continuous inventory and residue controllers (Fig.1). The lack controller uses the access rate as the control value for the stock, while the backlog uses the capacity of the work system. The deviation of the target/actual power is integrated over time and forms the basis for the calculation of the required power for residue minimisation. If the target stock balance deviates, the stock controller adjusts the access rate until the variances have vanished. Using this controller concept, throughput times and stock can be kept constant even under dynamic conditions by synchronising capacity and capacity.

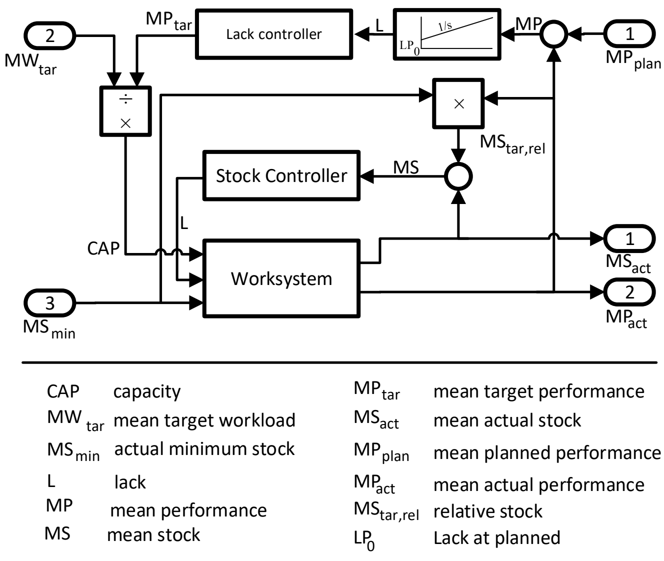

Fig. 1. Petermann's fundamental control-theoretic model [14]

In both feedback loops, there is have the same system which can be interpreted as the work system itself. It is shown in Fig. 2. At this point merely discuss the "performance curve" (PC) subsystem here, which is the core part of the model in the sense that it establishes a certain relationship between the stock and the performance of the work system. The PC defines how fast

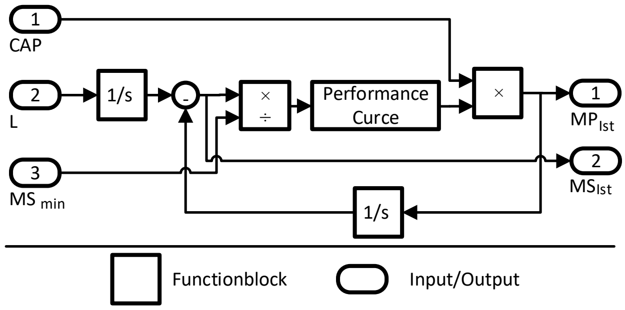

Fig. 2. The plant "work system" in Petermann's control-theoretic model Fig. 1

the current stock is processed by the machine.

Hofmann [14] shows the Petermann model implemented in the simulation software. In particular, he conceived the idea of implementing the PC as a linear feedback loop, for instance, a generic loop with a proportional–integral–derivative controllert (PID) controller to a second-order lag element (PT_2) element plant, as shown in Fig. 3. The advantage of a PT_2 function to represent the PC over the most commonly used first-order lag element (PT_1) function [14], is the possibility it allows for the real-time simulation of temporal behaviour. This allows PT_2 functions to be used, for example in model machines that have a capacity of greater than 100% over a short period of time.
Model machines that have a capacity of greater than 100% over a short period of time. The PT_2 element is a linear transfer element and in its easiest form mathematically defined by a second-order ordinary differential equation (ODE)

$$\ddot{y}(t) + 2\,d\dot{y}(t) + y(t) = u(t), \tag{2}$$

where y is the state and at the same time the output of the system, u is an input and $d > 0$ is the damping factor [15]. Introducing the state vector $x = [y, \dot{y}]^T$, we can rewrite this in the form of a *linear, time-invariant* system

$$\begin{aligned} \dot{x}(t) &= A\,x(t) + b\,u(t), \\ y(t) &= c^T\,x(t), \end{aligned} \tag{3}$$

with

$$A = \begin{bmatrix} 0 & 1 \\ -1 & -2d \end{bmatrix}, \qquad b = \begin{bmatrix} 0 \\ 1 \end{bmatrix}, \qquad c = \begin{bmatrix} 1 \\ 0 \end{bmatrix}. \tag{4}$$

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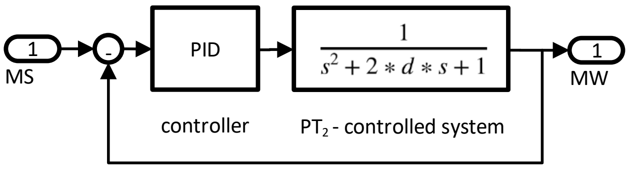

Fig. 3. Implementation of a PC with PT_2 behaviour

Alternatively, we can describe the PT_2 element in the frequency domain in terms of a transfer function

$$G(s) = \frac{1}{s^2 + 2d\,s + 1}, \qquad s \in \mathbb{C}. \tag{5}$$

Hofman [14] implemented an abrasion controller and a maintenance element in addition to Petermann's basic model of a work system. These functionalities enable the model to simulate an abrasion-driven decrease in the work system's maximum performance and to turn off the work system during a maintenance period, in the event that the maximum performance falls below a predefined threshold. Hofmann presented some convincing simulation results, considering practice-oriented events such as rush orders and capacity disturbances. Nevertheless, he could not find a satisfactory answer to the question of the system's stability.

Indeed, stability analysis is a poorly investigated discipline of PPC [10]. This may be due to the fact, that work system models, such as Petermann's and Hofmann's, typically turn out to be *nonlinear*, which is the reason why performing an appropriate stability analysis is a highly nontrivial task. The stability concept most widely known among engineers most commonly known stability concept, the *bounded-input, bounded-output* (BIBO) stability notion, fails in this situation, because standard tools such as the well-known *Nyquist criterion* [15] are only applicable to linear systems. For this reason, we present a new, mathematically correct approach to solve this problem here. In particular, we establish a relation between the stability of the PC and the system as a whole.

3. Methodology and main results

The method in this paper analysing the stability of the work system model basically consists of three steps. In the first step, the method apply certain simplifications to the model which shell enable us in the second step to deduce its mathematical representation in form of the nonlinear ODE system. In the third step, its shall briefly introduce the *input-to-state* stability (ISS) notion [16, 17], which we require here, due to the nonlinearity of the ODE system. In particular, we will state an appropriate version of the so-called *small-gain theorem*, which will be the major tool in proving of the ISS of the work system model.

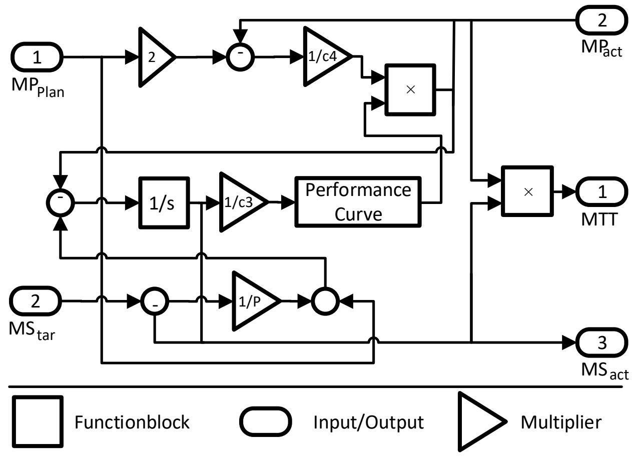

Fig. 4. Simplified model

The above-mentioned model offers the following simplifications:

- Assumption that the input signals MS_{min} and MW_{tar} to be constant, i.e., time-independent.
- The input signal MS_{tar} to be known immediately, i.e., we do not need to compute it $MS_{tar} = MS_{min}\,MS_{rel,tar}$ as depicted in Fig. 1.
- Reduction of the model about all Simulink blocks *Switch*.
- Renouncement of all parts of the model that implement the abrasion controller or maintenance element.

These simplifications should not affect the stability of the system. However, we will not be able to perform stability analysis with respect to the input signals MS_{min} and MW_{tar}, as they are assumed to be constant, on the basis of the first assumption above. As a result, we obtain the simplified model shown in Fig.4.

Now, it is possible to derive an ODE system that describes the simplified model in Fig. 4. Clearly, the form of this ODE system - in particular the number of states - depends on the implementation of the PC. In general, if the PC is a linear control system with system matrix $A = A_{PC}$ and input vector $b = b_{PC}$ (corresponding to (3)), the ODE system can be written as

$$\dot{x}_l(t) = A_{PC}\, x_l(t) + b_{PC}\, x_{nl}(t), \tag{6}$$

$$\dot{x}_{nl}(t) = -x_{nl}(t) + \frac{1}{c_1}\left(u_1(t) + u_2(t) - 2\,u_1(t)\,\frac{x_l^{(1)}(t)}{c_2 + x_l^{(1)}(t)}\right), \tag{7}$$

where

$$c_1 := MS_{min}, \qquad c_2 := MW_{tar}$$

are positive constants,

$$u_1 := MP_{plan}, \qquad u_2 := MS_{tar}$$

are the inputs of the simplified system, and $x_l^{(1)}$ is the first component of x_l which we take as $x_l^{(1)} = MW$. By definition, it holds that $x_l^{(1)}(t) = MW(t) \geq 0$ for all $t \geq 0$. As a consequence, on the right-hand side of (7), no division by zero can occur. If we assume that the PC has PT_2 behavior and omit the D part of the PID controller for the sake of computational simplicity, we obtain

$$A_{PC} = \begin{bmatrix} 0 & 1 & 0 \\ -(1+K_P) & -2d & 1 \\ -K_I & 0 & 0 \end{bmatrix}, \qquad b_{PC} = \begin{bmatrix} 0 \\ K_P \\ K_I \end{bmatrix}, \tag{8}$$

where $K_P, K_I > 0$ are the controller parameters, and d is the damping factor of the PT_2 plant, see formula (2).

Note that the simplified model can be considered as a coupled system of the linear subsystem (6) with the state x_l describing the PC and the scalar nonlinear equation (7) with the state x_{nl}. The two systems are coupled in the sense that the state x_{nl} of the nonlinear equation (7) is fed into the linear equation (6) as a so-called *internal input*. Conversely, the first state component $x_l^{(1)}$ of (6) serves as an internal input for the nonlinear equation (7). Accordingly, we henceforth refer to u_1 and u_2 as the *external inputs* of the system. Fig. 5 illustrates this setting.

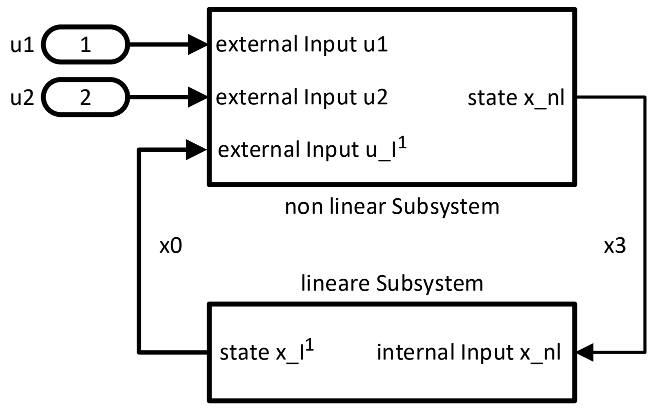

Fig. 5. Breakdown of the simplified model to a linear and a nonlinear part

Now that we have found a correct mathematical representation of the work system model, we must provide a suitable stability notion that can be applied here. As for nonlinear control systems, the so-called *input-to-state stability* is typically an appropriate choice [16, 17, 18].

Definition 3.1. *We define the function classes $\mathcal{K}$, $\mathcal{L}$ and $\mathcal{KL}$ as following.*

- *Class $\mathcal{K}$ is the set of all functions $\gamma\colon [0,\infty) \to [0,\infty)$ that are continuous, nondecreasing and which satisfy $\gamma(0) = 0$.*
- *Class $\mathcal{L}$ is the set of all functions $\alpha\colon [0,\infty) \to [0,\infty)$ that are continuous, nonincreasing and which satisfy $\lim_{t\to\infty} \alpha(t) = 0$.*
- *Class $\mathcal{KL}$ is the set of all functions $\beta\colon [0,\infty) \times [0,\infty) \to [0,\infty)$ that satisfy $\beta(\cdot,t) \in \mathcal{K}$ and $\beta(r,\cdot) \in \mathcal{L}$ for all $t, r \geq 0$.*

Definition 3.2. *A control system in the form*

$$\dot{x}(t) = f(x(t), u(t)), \qquad x(0) = x_0$$

is called input-to-state stable (ISS), if for all initial states x_0 and for all bounded (external) inputs u, there exist $\gamma \in \mathcal{K}$ and $\beta \in \mathcal{KL}$ such that the inequality

$$\|x(t)\| \leq \beta(\|x_0\|, t) + \gamma\left(\|u\|_{[0,t]}\right)$$

holds for all $t \geq 0$, where we denote

$$\|u\|_{[0,t]} := \sup_{0\leq\tau\leq t} \|u(\tau)\|.$$

The function γ is referred to as the (external) gain.

The main advantage of the ISS concept is the possibility if offers to analyse the stability properties of interconnected systems. We now introduce the corresponding tool, the so-called *small-gain theorem*, in a convenient manner.

Theorem 3.3. *Consider a control system Σ that consists of n pairwise interconnected systems $\Sigma_1, \ldots, \Sigma_n$ given by*

$$\Sigma_i : \qquad \dot{x}_i(t) = f_i(x_1(t), \ldots, x_n(t), u_i(t)), \qquad i = 1, \ldots, n,$$

where $u_1, \ldots, u_n$ are the external inputs. Assume these systems to be ISS with linear internal gains, i.e., there exist $\beta_1, \ldots, \beta_n \in \mathcal{KL}$, $\gamma_1, \ldots, \gamma_n \in \mathcal{K}$, and constants $\gamma_{ij} \geq 0$ with $\gamma_{ii} = 0$, $i, j = 1, \ldots, n$, such that for all $t \geq 0$ the inequality

$$\|x_i(t)\| \leq \beta_i(\|x_i(0)\|, t) + \sum_{j=1}^{n} \gamma_{ij} \|x_j\|_{[0,t]} + \gamma_i\left(\|u_i\|_{[0,t]}\right)$$

holds for $i = 1, \ldots, n$. Then Σ is also ISS, if the internal gain matrix

$$\Gamma = \begin{bmatrix} \gamma_{11} & \cdots & \gamma_{1n} \\ \vdots & & \vdots \\ \gamma_{n1} & \cdots & \gamma_{nn} \end{bmatrix}$$

satisfies the condition $\rho(\Gamma) < 1$, where $\rho(\Gamma)$ denotes the spectral radius of Γ, i.e. the largest absolute value of the eigenvalues of the matrix Γ.

We wish to apply the small-gain theorem for $n = 2$ to the interconnected system given by (6) and (7). In [18] it is shown that a linear control system in the form (6) is ISS, if it is asymptotically stable, i.e., if all the eigenvalues of its system matrix (in our case A_{PC}) have negative real parts. For the PT_2 example given by (8), this is the case if and only if it holds that

$$d > \frac{K_I}{2(1 + K_P)}. \tag{9}$$

Furthermore, the corresponding gain is a linear function $\gamma_l^{in}(r) = \gamma r$ for some $\gamma \geq 0$. For the nonlinear equation (7), we can directly prove that it is ISS. Indeed, introducing the notation $w(t) = \frac{x_l^{(1)}(\tau)}{c_2 + x_l^{(1)}(\tau)}$ for the nonlinearity and observing that $|w(t)| \leq 1$ for all $t \geq 0$, we have

$$|x_{nl}(t)| \leq e^{-t}|x_{nl}(0)| + \left| \int_0^t e^{\tau - t} \frac{1}{c_1} \left(u_1(\tau) + u_2(\tau) - 2u_1(\tau)w(\tau)\right) \mathrm{d}\tau \right| \tag{10}$$

$$\leq e^{-t}|x_{nl}(0)| + \frac{1}{c_1} \int_0^t e^{\tau - t} \left(3\|u_1\|_{[0,t]} + \|u_2\|_{[0,t]}\right) \mathrm{d}\tau \tag{11}$$

$$\leq e^{-t}|x_{nl}(0)| + \frac{4}{c_1} \|u\|_{[0,t]} \int_0^t e^{\tau - t} \mathrm{d}\tau \tag{12}$$

$$= e^{-t}|x_{nl}(0)| + \frac{4}{c_1} \|u\|_{[0,t]} (1 - e^{-t}) \tag{13}$$

$$\leq \underbrace{e^{-t}|x_{nl}(0)|}_{=:\beta(|x_{nl}(0)|,t)} + \underbrace{0 \cdot \|x_l^{(1)}\|_{[0,t]}}_{=:\gamma_{nl}^{in}\left(\|x_l^{(1)}\|_{[0,t]}\right)} + \underbrace{\frac{4}{c_3} \|u\|_{[0,t]}}_{=:\gamma_{nl}^{ex}\left(\|u\|_{[0,t]}\right)}. \tag{14}$$

Choosing β, γ_{nl}^{in} and γ_{nl}^{ex} suitably as shown above, we conclude that the nonlinear system is ISS and the corresponding internal gain is $\gamma_{nl}^{in} \equiv 0$. Thus, in this case, the internal gain matrix Γ from the small-gain theorem reads

$$\Gamma = \begin{bmatrix} 0 & 0 \\ \gamma & 0 \end{bmatrix},$$

which yields $\rho(\Gamma) = 0$. From the small-gain theorem, we have the following final result.

Theorem 3.4. *The simplified work system model is ISS, if the PC is asymptotically stable.*

An interesting interpretation of this result is that not only the ISS of the work system model follows from the stability of the PC, but also the BIBO (bounded input, bounded output) stability, i.e., it responds to the bounded inputs $u_1 = MP_{plan}$ and $u_2 = MS_{tar}$ with bounded outputs MP_{act} and MS_{act}. So far, we have not considered the output equations of the simplified model. These read

$$MP_{act}(t) = 2\, MP_{plan}(t) \frac{MW(t)}{MW_{tar} + MW(t)}, \tag{15}$$

$$MS_{act}(t) = MS_{min}\, MS_{rel}(t). \tag{16}$$

Suppose that the system is ISS and that the external inputs are bounded, then it follows from (3.2) and the properties of the function classes in Definition 3.1 that all the states are bounded as well. Considering the output equations (15) and (16), we see that the outputs are also bounded. As far as the output signal MS_{act} is concerned, this is obvious from the corresponding output equation (16). For the ouput signal MP_{act}, we have from the output equation (15)

$$|MP_{act}(t)| = 2\,|MP_{plan}(t)| \underbrace{\left| \frac{MW(t)}{MW_{tar} + MW(t)} \right|}_{<1}$$

$$< 2|MP_{plan}(t)| < \infty.$$

This result can easily be extended to a series of two (or more) work systems in the sense that the output signals MP_{act} and MS_{act} of the first system serve as input signals MP_{plan} and MS_{tar} of the second system and so on. These signals generally undergo a dead time, which simulates the transport time. The implementation of a series consisting of multiple work systems is shown in Fig. 6. If required, additional bearings can be added using integrals.

If all the work systems have stable PCs, then the series is BIBO stable. This can be verified by observing that if the first work system has a stable PC, it responds to bounded input signals with bounded output signals. Of course, the dead time element preserves the boundedness. The second work system responds with bounded output signals again, if it has a stable PC, and so on.

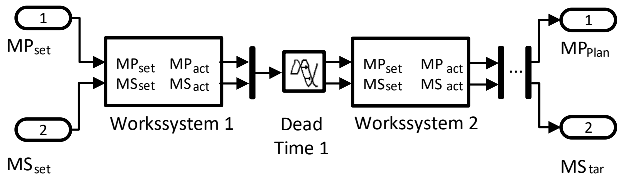

Fig. 6. SIMULINK implementation of a series of multiple work system models

4. Application

This section explains the prototypical realisation and evaluation of the model-based stability calculation in the case of the highly automated one-off production of spectacle lenses. These systems are linked by conveyor belts and perform up to 75.000 operations out on five systems per day, see Fig.7. These systems report their performance and any disruptions to a service in a cloud.

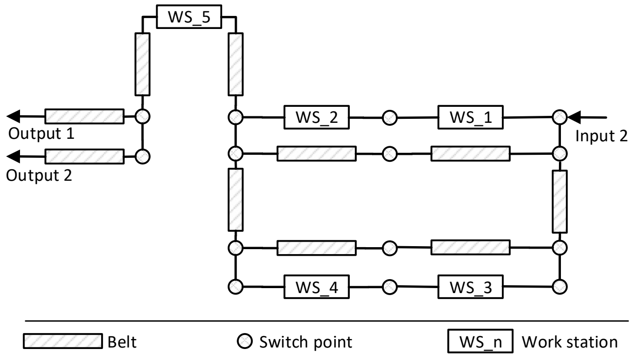

Fig. 7. Production system for glasses

Under certain circumstances, the system shown in Fig. 7 can be modelled as a series of work systems as shown in Fig. 6. We interpret the signals in the figure as currents of production orders, or the mean performance MP. Assume that all the orders pass each of the five work systems (WS_1 to WS_5, in that order) exactly once, we have a series of these five work systems from "Input" to "Output_1" or "Output_2", whereas the conveyor belts are modelled as dead times, as discussed before. If each of the five work systems is modeled using Petermann's or Hofmann's technique and each of the models exhibits a PC with PT_2 behaviour - specified by (8) -, the simplified ODE system describing the production has 20 states. If all these PCs are asymptotically stable, which can be investigated by means of the Nyquist criterion, for instance, the production system model as a whole is BIBO stable in the sense that for all bounded "Input" signals, the output signal "Output_2" is also bounded.

5. Service application

This section explains the prototypical realization and evaluation of the real-time forecasting service in the case of the highly automated one-off production of spectacle lenses. For technical reasons and the possibility of scaling hardware performance, a public cloud was chosen.

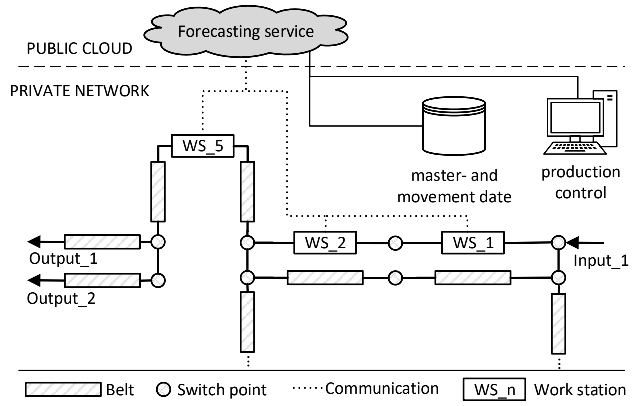

Fig. 8. Real-time forecasting service

The service operates a data exchange with

- master- and movement data,
- production resources (machines, warehouses and transport units) and
- production control.

The forecasting service starts with the production planning of orders. For this, the current information on order processing is used to create a total transfer function, see Fig.8. In order to form these, the required production resources are extracted from the production plan in a first step. In a second step, the parameters from the master data are entered into the PT_1, PT_2 and deadtime elements. Third, the overall transfer function is updated with the current state of the production machines (WS_1, WS_2 and WS_5). This includes the e.g. the maximum production capacity. Each of these listed production machines corresponds to a transfer function as shown in formula (5).
Now all parameters of the overall transfer function (17) are determined and can be calculated in the cloud. The function (17) include all production elements from Input_1 to the two Outputs.

$$G(all) = \frac{WS_1 * WS_2 * WS_5}{1 + WS_1 * WS_2 * WS_5} \quad (17)$$

The result of the calculation gives an indication of how stable the current production will be. Initial applications show that a low stability in a longer turnaround time. Here is a strong connection to see. The user can view the values of stability and adjust the production control accordingly.
This service was realized with a service in the cloud. In the cloud, every new event like changes in order sequence or machine control performed a new calculation of the stability of production in a service. To transfer the information from the machines to the service, the protocol OPC UA (Unified Architecture) is used. As described in DIN SPEC 92222, different protocol and communication types can be used.

6. Summary and outlook

This section explains the prototypical realization and evaluation of the real-time forecasting service in the case of the highly automated one-off production of spectacle lenses. For technical reasons and the possibility of scaling hardware performance, a public cloud was chosen. The service operates a data exchange with master and movement data, production resources (machines, warehouses and transport) and production control. The forecasting service starts with production planning. For this purpose, the current information about the order processing is used to create a total transfer function. In conclusion, the states of the machines are added to the PT_2, the transport times and the stocks. In the cloud, every new event like Changes in job order or machine control performed a new calculation of the stability of the production.

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