A Simulation Model for the Closed-Loop Control of a Multi-Workstation Production System

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Abstract

In this paper, we propose a simulation model with a PI controller to analyze and control the dynamics of a multi-workstation production system. The formulation is based on dynamic modelling and control theory, and the model was implemented in Matlab and Simulink. Exploratory tests were carried out, and the results indicated some relationships between the values of the parameters of the controller and the values of the output variables, that is, the levels of work in process. They also showed that the proposed model has the potential of providing managerial directions on how to dynamically adjust the capacity, aiming to smooth the operation of the shop floor and to keep the work in process close to the desired levels.

Keywords: production systems, control theory, dynamics, simulation, planning and scheduling

1 Introduction

As known, the increasing computational capacity engendered a sound evolution of the operations management area, since it allowed the development of several tools to cope with large amounts of data related to the planning process and to ground the analysis of the decision makers. In this sense, the use of dynamic modeling and simulation techniques complements the static approaches for planning optimization of production systems and supply chains. Control theory is also a correlated area whose theories and tools have been applied to production and supply chain management. Some steps in these directions are enumerated in the literature review section of this paper.

Considering the aforementioned approaches, we present in this paper a simulation model based on state equations to depict the dynamics of a multi-workstation manufacturing system. A proportional-integral (PI) controller is applied to the model, and exploratory tests are carried out.

The model basically deals with the work in process (WIP) and capacity allocation variables (represented by the processing frequency of the stations), in a plant with job shop configuration. In general terms, the control of work in process is a classical concern in the operation of job shops, since it generates more predictable cycle/throughput times, which lead to better promises and fulfilment of delivery dates, a more stable coordination of the shop floor, and more flexibility to attend changes in the customer demand. These effects are highlighted in the literature related to various methodologies in production engineering, such as just-in-time, quick response manufacturing, workload control, factory physics, and others.

The results obtained with the simulation of the proposed model provided some indications of how its parameters influence the WIP levels, and demonstrated the potential of the proposed approach to depict the dynamic relations between capacity allocation, work in process and operations smoothness in production systems.

2 Literature Review

The effort of evolving from the static to the dynamic analysis of production and supply chain systems relies on system dynamics and control theory, as mentioned. In a broader sense, system dynamics may be defined as an area of knowledge that deals with the time-varying behavior of a system (Doebelin, 1998). This includes not only mechanical, electrical, fluid and thermal, but may also include biological, manufacturing, social and hybrid systems. Control theory, on its turn, has different subareas and a range of tools for the analysis and design of closed-loop systems, where the information of the outputs is fed back to the system in order to lead it to desired goals. In the literature reviews concerning the application of control theory to production and supply chain, the models are classified according to the area of application [(Ortega and Lin, 2004), (Sagawa and Nagano, 2015b)], the underlying control methodology (Sarimveis et al., 2008), the type of analysis that is carried out (i.e. robustness, stability, etc.) (Ivanov and Sokolov, 2013), or according to mixed criteria (Åström and Kumar, 2014).

In Table 1, we present some applications of control theory to production and supply chain systems, classified according to subareas of application and the methods underlying the models. Our intention here is not to present an extensive review, but rather to enumerate different possibilities and to provide few references in each category, as examples.

Other applications based on model predictive control or robust optimal control are not listed here, but can be found in (Sarimveis et al., 2008). Also, there are some alterna-

Table 1. Some Applications of control theory in production systems and supply chains

Area/type of application	*Applied methodologies and tools*	*References (examples)*
single-product production-inventory models and extensions to supply chain	classical control theory, block diagrams, transfer functions	(Towell, 1982; Zhou et al., 2006; Spiegler et al., 2016)
production-inventory models with single and multiple-machines (with or without additional constraints)	dynamic programming and optimal control	(Scarf, 1960; Boukas and Liu, 2001; Gharbi and Kenne, 2003)
multi-echelon production-inventory models using bills of material as input	input-output analysis, Laplace or z-transform, probability distributions, NPV	(Axsäter, 1976; Grubbström and Molinder, 1994; Grubbström et al., 2010)
multiple-machine and multi-product systems based on flow models	flow models, block diagrams, transfer functions, bond graphs	(Wiendahl and Breithaupt, 2000; Kim and Duffie, 2006; Sagawa and Nagano, 2015a)
supervisory/process control of continuous production systems and its integration within the hierarchical production planning	mixed integer dynamic optimization (MIDO), mixed integer nonlinear programming (MINLP)	(Monfared and Yang, 2007; Munawar and Gudi, 2004; Du et al., 2015)
production and supply chain models with autonomous control/decentralized agents	queue length estimator (QLE), pheromone, heuristic methods, RFID	(Scholz-Reiter and Freitag, 2007; Wang and Lin, 2009; Barenji et al., 2014; Schukraft et al., 2016)

tive formulations out of the control theory area, based, for instance, in queueing systems, which are out of the scope of this paper.

In the following subsection, we present the mathematical model that was adopted as basis for the simulation model proposed in this paper.

2.1 Dynamic multi-workstation model based on electrical components

A dynamic model based on the ideal properties of electrical components is proposed in (Sagawa and Nagano, 2015a) to depict a multi-workstation system that can manufacture different families of products. The model is basically composed by machines, buffers and junction elements.

The machines are compared to resistors and their processing frequency U_i correspond to $\frac{1}{R}$, where R is an ideal resistance. Similarly, the buffers are seen as ideal capacitors with capacitance C, which corresponds to their storage capacity (Ferney, 2000). The junctions are used to couple these manufacturing elements and to depict the configuration of the production flow in the system, i.e. to represent the different process routings of each product or product family (Sagawa and Nagano, 2015a). When a given machine outputs flow to m workstations downstream, it is coupled to these workstations by means of a divergent junction that imposes the conservation of flow. Similarly, the upstream flows coming from different workstations to a given workstation are merged by means of a convergent junction that conserves the total flow (Sagawa and Nagano, 2015a; Ferney, 2000). The discussed model is continuous and deals with 3 variables: the production flow f, the production volume q and the effort e. The production volume corresponds to the integral of the flow, and the effort is used as an auxiliary variable, for coupling a machine and its precedent buffer, as well for the approximation of a discrete system as a continuous system (Ferney, 2000). The basic equation of the model is derived from the well-known constitutive equations of the ideal electrical components previously mentioned, and is shown in (1). The variables and parameters of this equation were already mentioned in the text. The index i denotes a given workstation, the index s applied to the flow or effort variables denotes the output of this station, and the index e denotes its input. Eq. (2) is based on the aforementioned integral relation between the production volume q and the flow variable f, likewise the electric charge stored in a capacitor is defined as a function of the integral of the electric current. In the context of manufacturing, $\dot{q}_i(t)$ is interpreted as a rate of material storage or consumption, expressed as the difference between the input and output flow of a workstation.

$$f_{si} = U_i \left[\frac{q_i(t)}{C_i} + \min\{1, q_i(t)\} - e_{si}(t) \right] \quad (1)$$

$$\dot{q}_i(t) = f_{ei}(t) - U_i \min\{1, q_i(t)\} \quad (2)$$

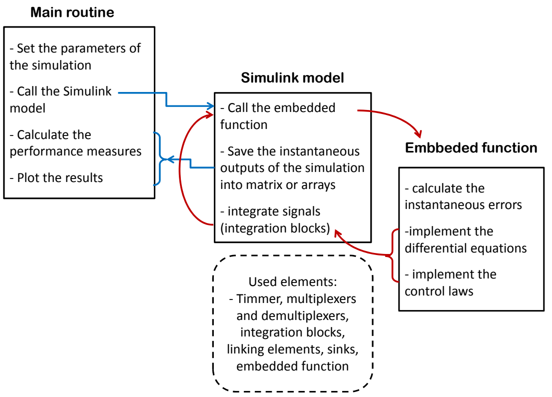

Figure 1. Schematics of the simulation model

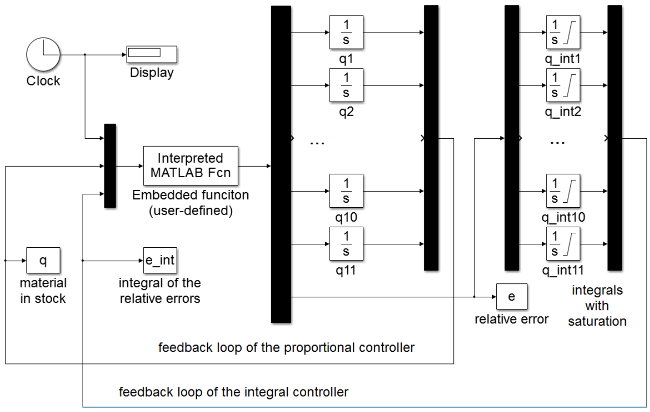

Figure 2. Schematics of the model build in Simulink®

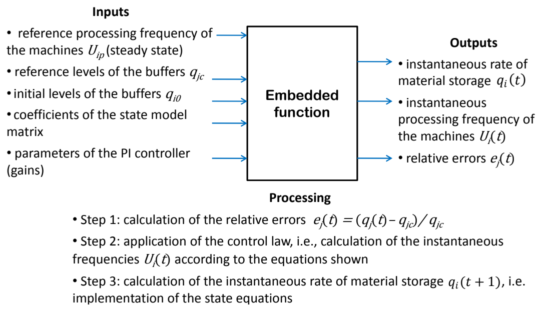

Figure 3. User-defined function implemented in the simulation model

The assumption of buffers with unlimited capacity allows simplifying (1), and the combination of (1) and (2) yields the basic state equation of a workstation, presented in (3).

$$\dot{q}_i(t) = f_{ei}(t) - U_i \min\{1, q_i(t)\} \tag{3}$$

This basic equation and the constitutive equations of the junctions were applied to a 11-workstation production system, as presented in (Sagawa and Nagano, 2015a), resulting in the state model shown in (4).

$$\begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \\ \dot{q}_4 \\ \dot{q}_5 \\ \dot{q}_6 \\ \dot{q}_7 \\ \dot{q}_8 \\ \dot{q}_9 \\ \dot{q}_10 \\ \dot{q}_11 \end{bmatrix} = \begin{bmatrix} -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.4300 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.2508 & 0.5118 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.1538 & 0.3140 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.0170 & 0.0347 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.0175 & 0.0020 & 0.2811 & 0.2811 & 0 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0.0087 & 0.0010 & 0.1399 & 0.1399 & 0 & 0 & -1 & 0 & 0 & 0 \\ 0 & 0.0161 & 0.0018 & 0.2588 & 0.2588 & 0 & 0 & 0 & -1 & 0 & 0 \\ 0 & 0.0200 & 0.0023 & 0.3204 & 0.3204 & 0 & 0 & 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.2407 & 0.2407 & 0.2407 & 0.2407 & -1 \end{bmatrix} \begin{bmatrix} U_1 \min\{1,q_1\} \\ U_2 \min\{1,q_2\} \\ U_3 \min\{1,q_3\} \\ U_4 \min\{1,q_4\} \\ U_5 \min\{1,q_5\} \\ U_6 \min\{1,q_6\} \\ U_7 \min\{1,q_7\} \\ U_8 \min\{1,q_8\} \\ U_9 \min\{1,q_9\} \\ U_{10} \min\{1,q_{10}\} \\ U_{11} \min\{1,q_{11}\} \end{bmatrix} + \begin{bmatrix} U_{01} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{4}$$

3 Simulation Model with a PI Controller

A simulation model based on the presented state equations was implemented using Matlab® and Simulink®. It included a proportional-integral (PI) controller, as mentioned. The structure of this model, as well as the executed instructions, are shown in Fig. 1. As it can be seen, the relevant parameters of the simulation are defined in the main routine. After that, this routine calls the Simulink model (Fig. 2), which contains the block diagram of the dynamic model with the controller. The computation of the state equations is performed by a user-defined function embedded in the Simulink® model.

After the iterations are carried out for the total simulated time, the main routine compiles the results and calculates the performance measures. For the implementation of a proportional-integral controller, integration blocks $(1/s)$ of the first level should be applied to the instantaneous material storage rates $\dot{q}_i$, while second level integrations should be applied to the relative errors in the stock levels, as it can be seen in Fig. 2.

As mentioned, the state model is implemented by means of a user-defined function. The inputs of this function are those parameters defined in the main routine, and presented in Fig. 3.

With these inputs, the function calculates, at each time t, the relative errors of the stock levels, shown in (5), and implements the control law. For an integral controller, this control law is shown in (6). With the values of the instantaneous processing frequencies of the machines U_i, resulting from the implementation of the control law, the instantaneous rates of material storage $\dot{q}_i(t+1)$ are then calculated. These rates are integrated in the integration blocks and fed back to the model

$$e'_j(t) = -e_j(t) = \frac{q_{jc} - q_j(c)}{q_{jc}} \tag{5}$$

$$U_i(t) = U_{ip}\left(1 + k_p e'_j(t) + k_i \int e'_j(t)dt\right) \tag{6}$$

where $\dot{q}_j(t)$ is the instantaneous amount of material stored in buffer j, $e'_j(t)$ is the relative error considering the actual level $\dot{q}_j(t)$ and the reference level q_{jc};U_{ip} is the reference for the processing frequency of machine i, considering the customer demand fulfillment in the steady state; k_p is the proportional gain of the controller; and k_i is the integral gain. The presented equations apply for the case where the buffer j immediately succeeds the machine i. If machine i is succeeded by more than one buffer, the minimum value of e_j is computed.

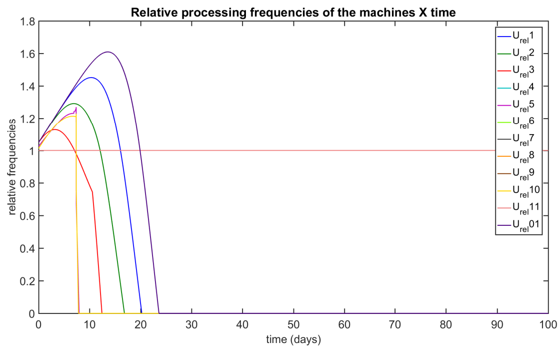

Figure 4. Processing frequencies of the machines for a test carried out with $k_p = 0.05$ and $ki = 0.05$ (whitout saturation limits).

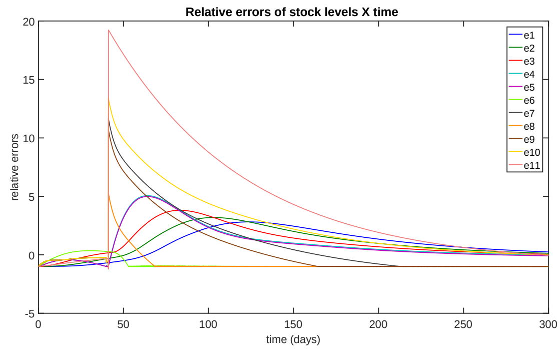

Figure 5. Evolution of the relative errors in stock levels (WIP), for saturation limits of ± 10, $k_p = 0.05$ and $k_i = 0.001$.

4 Test and Results

The proposed simulation model was applied to the 11-workstation system presented in (Sagawa and Nagano, 2015a). For an initial analysis, it was of interest to consider the warm-up of the manufacturing system and its transition to the regular operation, that is, to consider the situation where all the buffers are empty ($qi0 = 0$ for all i) and the system starts to work, aiming to attend the customer demand and to reach the desired levels of work in process. This starting condition is somewhat similar to the application of a step input, conventionally used for the study of the response in dynamic systems. In our case, however, each buffer has a different reference level, since these levels were defined as a multiple of the amount of material cumulated in each buffer when the system was simulated without control, i.e., when the open-loop system was simulated. In order to allow comparisons, we adopted a multiplication factor of 100 times, as in (Sagawa and Nagano, 2015a). As output variables of the tests, we analyzed the values of the processing frequencies of the machines $U_i(t)$ (the controlled variables); the relative processing frequencies, i.e. $(U_i(t) - U_{ip})/U_{ip}$; and the relative errors in the buffer levels (e_i) over time. This last measure indicates the variation of the work in process in the system. Depending on the selected values of the gains, the machines are led to operate with processing frequencies above the reference frequencies, in order to fulfill the buffers. In Fig. 4, the source of material works with a processing frequency that is 60% greater than the frequency that attends the customer demand in the medium term, i.e. in the steady state. This control command generates a surplus of material in the buffers. When the controller receives this information, it reduces the processing frequency of the machines. This reaction, however, is excessive, so that the machines are shutdown. The saturation of the integral controller could be a relevant parameter of influence for the control of the processing frequencies of the machines. Due to the saturation in PI controllers, the integrator may drift to undesirable values, since it tends to produce progressively larger control signs. This effect is known as windup of the integral controller (F Franklin et al., 1994; Moreno-Valenzuela, 2008). Therefore, additional tests were performed with the establishment of saturation limits for the integral controller. Some results are shown in Fig. 5-8. The values of the gains were kept constant and different saturation limits were tested.

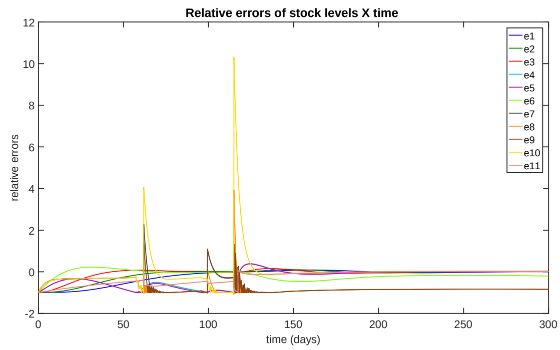

Figure 6. Evolution of the relative errors in stock levels (WIP), for saturation limits of ± 1, $k_p = 0.05$ and $k_i = 0.001$.

The presented results indicate that, with narrower saturation limits, the overshoots in the WIP (represented by the relative errors) were significantly reduced. In Fig. 5, the overshoot is of 20 times the reference level and in Fig. 5, it is of 10 times. Although punctual instabilities in the control of some machines arose (Fig. 7), the operation of the system also became smoother with the estab-

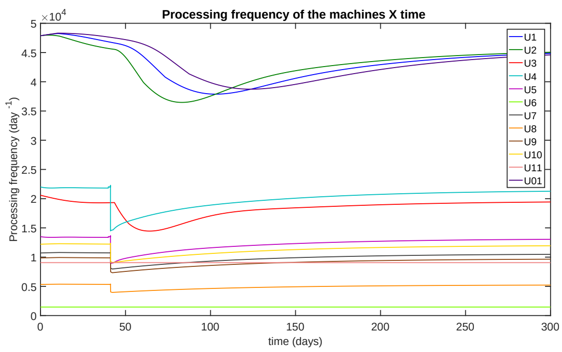

Figure 7. Evolution of the processing frequency of the machines, for saturation limits of ± 10, $k_p = 0.05$ and $k_i = 0.001$.

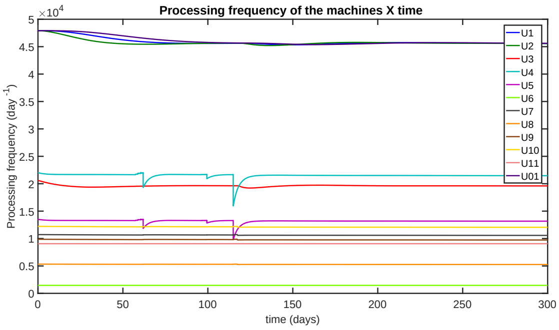

Figure 8. Evolution of the processing frequency of the machines, for saturation limits of ±1, $k_p = 0.05$ and $k_i = 0.001$.

lishment of saturation limits.

The exploratory tests have also shown that the overshoot in the processing frequencies of the machines tend to increase with the increase of the integral gain. Hence, the results could be further improved by means of systematic experiments and the application of control tools for the optimization of these parameters (gains and saturation limits).

From the managerial perspective, the controller can lead the system to undesired operating points, depending on parameters set, because working either too far above or below the regular capacity imply higher operational costs. Moreover, there are well-known relations among WIP, cycle times and throughput rate. An increase in WIP may engender a relevant increase in the cycle time (lead time), without producing any effect in the throughput rate of the production system (Hopp and Spearman, 2001). Longer cycles times usually result in delayed jobs, rush orders, and difficulty of coordination. Based on the aforementioned reasons, it is of interest, in our model, to find the parameters that enable to reduce the overshoot of WIP and, meanwhile, to reduce the oscillations in the processing frequencies of the machines.

The variations in the processing frequencies represent, in fact, capacity additions or reductions. Thus, the proposed simulation model may provide insights on how much capacity should be increased or decreased over time in order to: 1. guarantee adequate levels of WIP, to absorb fluctuations; 2. avoid an excessive increase in the cycle/throughput times; 3. smooth operations, so that the operational costs stay low. These capacity adjustments can be implemented in various ways, i.e. overtime, subcontracting, adding/renting extra resources, or reducing the utilization of the machines.

In practice, the goal of production managers is to keep the operations stable, as much as possible, so that no extra costs are incurred (although this pursuit of stability should not unreasonably compromise the flexibility to attend customers). In MRP systems, the short term variations in the plans are usually smoothed or prevented by applying time fences to demand, planning and/or order release. This solution is efficient to keep the costs under control, but disregards the dynamics of the production systems, so that backorders and stock outs in the short term may occur. In this sense, the use of the dynamic modeling and simulation seems to be an interesting alternative or complement to other methodologies used in the production engineering area. The presented formulation is also relatively simple and easy to implement, which is an advantage in terms of use.

In order to implement it, the production system under consideration must be first modeled according to the methodology proposed in (Sagawa and Nagano, 2015a), which requires data related to the production routings, the historical demand for the end products, the product mix and the capacity of the machines (for more details, please refer to (Sagawa and Nagano, 2015a)). The mentioned methodology presents a generalization capability due to its modularity. The basic manufacturing entities, each one associated to its respective constitutive equation, may be arranged to represent different shop floor configurations, such as single machine, parallel machines, flow shop, job shop and open shop. The resulting state model will be a combination of the expressions that represent the involved entities. After this model is defined and implemented in a software for dynamic simulation of continuous systems, the adequate parameters of the controller must be defined, aiming to reduce the WIP levels and to smooth the oscillations. The generalization of the presented model requires an endeavor in this direction, since for each particular manufacturing system, a different type of controller with specific tuning could provide the best results. Thus, the control synthesis for different manufacturing systems is still an issue to be tackled.

The analysis of the results, especially in terms of the relative processing frequencies of the machines, show how much and when the capacity of each workstation should be increased or reduced, in order to achieve the desired levels of WIP. One practical limitation of the model refers to the level of aggregation of the data. Therefore, it can indicate that, for a certain period of time, a given station should work 5% above its regular capacity, but it does not give indications regarding the detailed scheduling level, i.e. indications about which specific jobs/products to process with this extra capacity, in which sequence, and so on. In other words, the model is suitable for the planning level, instead of for the detailed execution level. In order to overcome this limitation, it could be used together with discrete event simulation models, or future efforts could be undertaken towards incorporating variables that concern the scheduling level, such as set up times of the machines or processing times of individual jobs.

5 Final Remarks

In this paper, we proposed a closed-loop simulation model with a PI controller to depict the dynamics of multi-workstation production system. The model was implemented and simulated in Matlab® and Simulink® considering the warm-up of the system, when the initially empty buffers should be filled to desired levels, while the medium-term customer demand is fulfilled.

The results of exploratory tests showed that the saturation limits of the integral controller exert a relevant influence in the reduction of the work in process, but may also introduce some punctual instabilities. In future works, this parameter and the gains of the controllers could be simultaneously optimized, by means of the application of control theory tools and the execution of systematic experiments.

In terms of operations management, the proposed simulation model has the potential to give prescriptive directions about the dynamic adjustment of the capacities, in order to keep the WIP in the desired levels and the production costs relatively low, when the smoothing of capacity variations is set as a goal. In conventional production planning and control systems, based on MRP, the short term variations in production are avoided by means of the implementation of time fences to demand, planning or order release, disregarding the dynamics of the system and its ability to react to disturbances. In this sense, the presented tool can complement the existing tools for analysis and control of production systems and supply chains, allowing to take the perspective of the dynamics into consideration.

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