COMBINED SYNTHESIS/SIMULATION APPROACH TO DESIGN AND VERIFICATION OF PRODUCTION CONTROL STRATEGIES

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ABSTRACT

Model based approaches to production control have been discussed in a variety of sources. Several attempts to derive production models by data mining and machine learning techniques have been reported recently. A more classical approach is to develop a discrete simulation model and explore various control scenarios in simulation setting. Another line of research explores the usability of analytical models in combination with standard control design techniques. More specifically, an application of bond graph modelling to a multi-product manufacturing system is reported in the literature. During the modelling process the discrete production dynamics is "fluidised" and analytical model is derived in matrix form. This paper extends the previous work in the sense that analytical model is used to tune the PI production controller and, for verification purposes, the discrete event simulation is applied, which renders a more realistic representation of discrete production dynamics. Among others, various disturbances in the planned production and their effect on the performance of the developed control strategy are more easily evaluated this way.

Keywords: Manufacturing systems, modelling, simulation, production control

1. INTRODUCTION

Contemporary manufacturing systems are characterized by flexibility and are dynamic multiproduct manufacturing systems operating in volatile environment. Related management methods are complex and can significantly benefit from computer support techniques including modelling and simulation.

Model based approaches to production control have been discussed in a variety of sources. Related modelling approaches are developing in line with the evolution from static deterministic to dynamic stochastic analysis of these systems. Viswanadham and Narahari (1992) state that mathematical modelling plays a vital role in the design, planning and operation of FMSs. They give a review of performance evaluation techniques of FMSs using stochastic modelling by Markov chains, queueing networks, and stochastic Petri nets. Further review on applications of queuing theory based techniques in manufacturing is given by Papadopoulos and Heavey (1996). Numerous works use discrete-event simulation for analysis and optimization of manufacturing systems. Longo (2013) proposes a simulation-based tool for solving short period production planning problem within a real manufacturing system. Jain et al. (2017) discuss manufacturing data analytics based on a virtual factory representation, which includes multi-resolution modelling capabilities.

A large number of works is applying Petri nets (PNs) for modelling various aspects of FMSs. In Recalde et al. (2004) a set of examples is collected illustrating the use of PNs for performance evaluation, performance control in terms of schedule optimization, modelling production management strategies, such as Pull Control and Kanban and also deadlock prevention techniques. Among others, hybrid models are discussed where discrete event view is combined and/or substituted by continuous view. Discrete state is relaxed into continuous variables, which opens the way to dynamic performance analysis of manufacturing systems as well as application of control design techniques.

Glavan et al. (2013) present an approach where a manufacturing performance model is derived from historical data on key performance indicators (KPI). Data mining techniques are used to derive a prediction model that is used in model predictive control setting for selected target KPI values.

A more classical approach is to develop production control strategies using analytical models in combination with standard control design techniques. Wiendahl and Breithaupt (2000) use a continuous flow model of a single work centre and develop a backlog controller and a work-in-process controller. Ortega and Lin (2004) present a review of control theoretic methods applied to production-inventory systems with classification of the used models and discuss their integration into production management hierarchy. A recent review of control theoretic approaches to production control is given by Duffie et al. (2014).

Another approach is to develop a dynamic simulation model and explore various control scenarios in a simulation setting. Sagawa et al. (2017) apply bond graph modelling to a multiproduct manufacturing system. During the modelling process the discrete production dynamics is "fluidised" and an analytical model is derived in matrix form. In Sagawa and Freitag (2016) the model is used to explore PI-controller-type production control strategies by simulating a closed loop model.

This paper extends the previous work of Sagawa et al. (2017) in the sense that the analytical model is used to tune the PI production controller and, for verification purposes, the discrete event simulation is applied, which renders a more realistic representation of discrete production dynamics. Among others, various disturbances in the planned production and their effect on the performance of the developed control strategy are more easily evaluated this way.

2. MODELLING OF THE MANUFACTURING SYSTEM

The modelling of manufacturing system in this paper follows the approach of Sagawa and Nagano (2015), Sagawa et al. (2017). The model depicts the dynamics of multi-product manufacturing system and was developed based on bond graph methodology. This brings the advantage of modularity, which allows the integration of different systems, subsystems and components. A dynamic model is developed representing the actual work in process (WIP) and actual production quantity over time. The objective of this dynamic modelling is to keep the WIP levels of the production system under control, even when the system faces disturbances. Bond graphs modelling allows an easy implementation of closed loop models. Hence, different automatic control strategies may be implemented and evaluated, grounded in a systematic dynamic analysis.

In order to develop the bond graph multi-product model, the steps of the general methodology for dynamic modelling (Doebelin 1998) were followed. To apply these to a manufacturing system, however, some issues had to be resolved, such as: how to represent multiple products in the bond graph model; and how to define the constraints of the problem, i.e., how to incorporate the data related to the multiple products in the model. The related solutions are described in Sagawa et al. (2017). Here, only an illustrative manufacturing system will be presented with a corresponding matrix model derived by the described methodology.

The model is a simplified version of the multi-station and multi-product model used in the aforementioned works. The example is based on real manufacturing system and can be considered as a stage in the manufacturing process of polymer bags and fabric in a textile company (Figure 1).

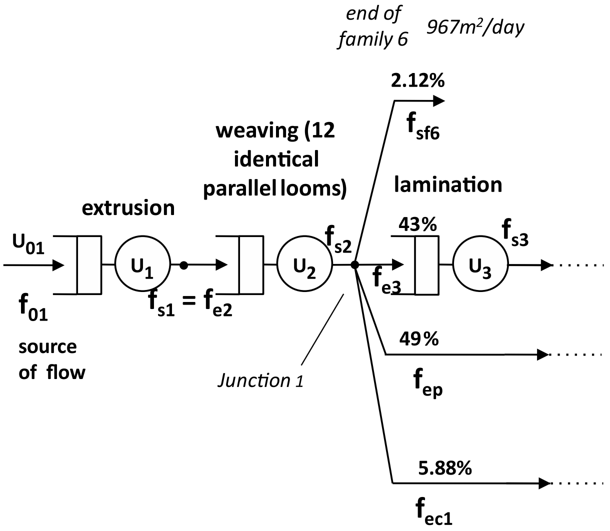

Figure 1: A stage in manufacturing system

The process starts with the extrusion of the polymer. The molten mix is forced out through the die head into a cooling tank, in the form of a film. After quenching, the film is slit into tapes by a row of equally spaced blades. The resulting tapes are stretched and annealed by passing them over and under a set of rolls. The finished tape yarns are then wound onto packages (bobbins). The weaving of the polypropylene tapes is done in circular looms, which can produce tubular cloth of various widths. Depending on the specifications of the products, this cloth goes through different finishing processes, such as printing or lamination.

The model of the described manufacturing stages in matrix form is shown in equation (1)

$$\begin{bmatrix} q_1' \\ q_2' \\ q_3' \end{bmatrix} = \begin{bmatrix} -1 & 0 & 0 \\ 1 & -1 & 0 \\ 0 & 0.43 & -1 \end{bmatrix} \cdot \begin{bmatrix} U_1 min(1, q_1) \\ U_2 min(1, q_2) \\ U_3 min(1, q_3) \end{bmatrix} + \begin{bmatrix} U_{01} \\ 0 \\ 0 \end{bmatrix} \qquad (1)$$

where q_1 to q_3 is the instantaneous production volume stored in the three buffers of the system, U_1 to U_3 are the processing frequencies of the workstations, and U_{01} is the processing frequency of the source of raw material that feeds the system. The term $min(1, q_i)$ is the result of fluidization of material flow, which is inherently discontinuous. The expression enables to properly handle the material flow in case a buffer is empty, see Sagawa and Nagano (2015) for details.

3. PI PRODUCTION CONTROL STRATEGY

The control strategy under investigation aims at maintaining the required buffer levels to meet the demanded daily production quantities of different product families. Figure 1 shows the target for one product family ($967m^2/day$), the other targets are defined further along the stages of manufacturing process. Nevertheless, the shown flow percentages in *Junction 1* indicate steady state material flow requirements. E.g. the source flow must correspond to 45548 m^2/day, which is also the steady state processing frequency of workstation 1 and workstation 2. The steady state processing frequency of workstation 3 corresponds to 43% of the total flow.

In order to achieve the desired WIP levels in the plant, the processing frequencies can be varied around steady state values. A suitable control law must be applied, and this was studied in Sagawa and Nagano (2015), Sagawa et al. (2017) and Sagawa and Freitag (2016). Among others,

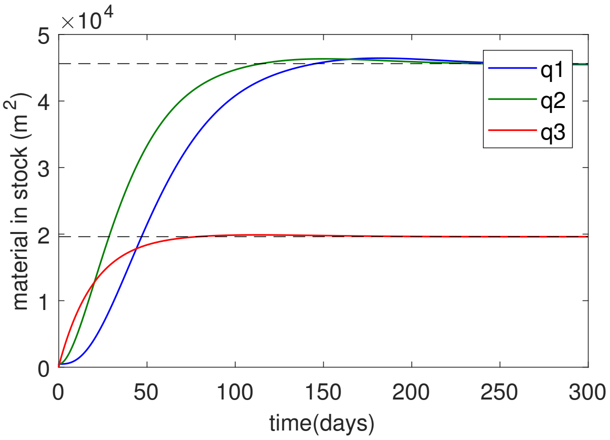

Figure 2: Building of WIP when starting with empty buffers

PI controllers were investigated in Sagawa and Freitag (2016). The controllers operate based on the normalized error

$$e_j = \frac{q_{jc} - q_j}{q_{jc}} \tag{2}$$

where q_{jc} is the desired buffer level, and q_j is the actual buffer level at position j. The control output is interpreted as a relative deviation from the steady state processing frequency. The actual processing frequency is determined by

$$U_i = U_{ip}(1 + u_{jPI}) \tag{3}$$

where U_{ip} is the steady state processing frequency of workstation i, and u_{jPI} is the control output calculated on the basis of level error in buffer j. In the case of linear material flow the processing frequency U_i is influenced by the level of first buffer downstream of workstation i. In case of parallel branches, the minimal control output of the corresponding controllers is considered.

Figure 2 shows the initial building of WIP when starting with empty buffers, until the processing frequencies stabilize at required material flows. Corresponding processing frequencies of workstations 1 and 2 as well as input flow U_{01} are shown in Figure 3. Note that processing frequency of workstation 3 is kept constant at steady state value U_{3p} and is not shown in the figure.

Figure 4 shows the WIP levels when the process operation is disturbed by temporary breakdown of workstation 2. The shown responses are obtained by continuous system simulation in Simulink where equation (1) is implemented and corresponding PI controllers are added.

In accordance with Sagawa and Freitag (2016) the controller parameters are set to $K_p = 0.05$ and $K_I = 0.001$. The integrator state was limited at ± 1.

4. DISCRETE EVENT SIMULATION BASED VERIFICATION

Continuous simulation is well suited to testing control strategies and controller tuning, yet the operation of the production system involves discrete operations. The question is how well the abstract continuous dynamic

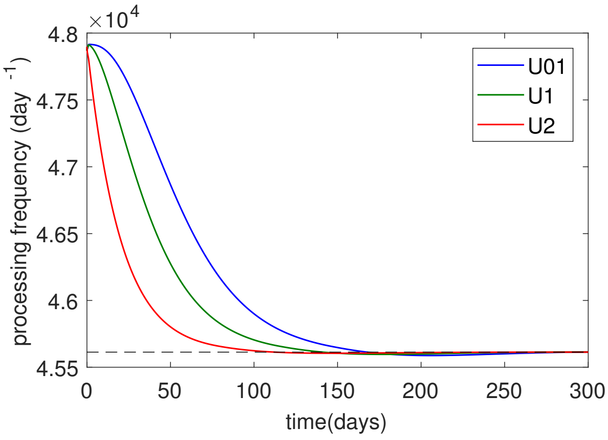

Figure 3: Adjustments of processing frequencies and material input flow

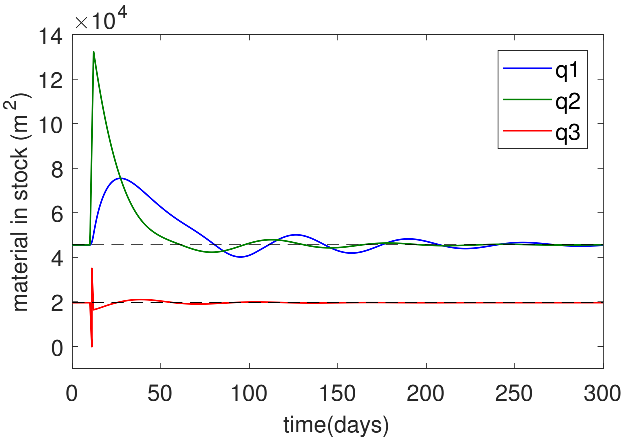

Figure 4: WIP levels at temporary workstation 2 breakdown

model represents the actual production dynamics. A partial answer to that can be obtained by verifying the developed production control strategy in discrete-event simulation (DES) setting.

A DES model was developed in SimEvents, a discrete-event simulation add-on to Simulink. The production system is represented as a network of queues and servers, and SimEvents permits to link the entity generation rates and server service rates to external signals, which can originate from continuous simulation. This way the derived PI control strategy can be tested also in DES setting. Still, some adjustments of the PI controllers are required to obtain comparable results. Firstly, a pure continuous implementation of the controllers is not feasible, since the buffer levels do not change continuously. This would also not be realistic considering potential industrial implementation, where on-going adjustments of the workstation processing frequencies would be impractical. Instead it was decided to determine the frequencies on a daily basis, which corresponds to discrete-time implementation of the PI controller with sampling time of 1 day. Secondly, the discrete-time implementation required an alternative implementation of the integrator saturation, which was introduced in continuous version to prevent integral controller windup.

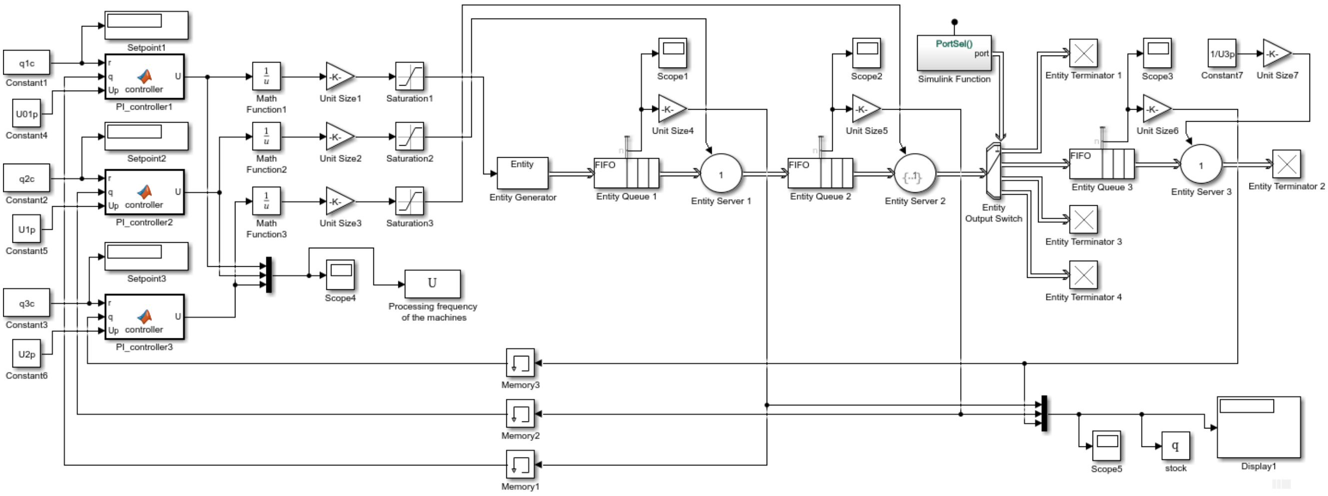

Figure 5: Simulation scheme - DES simulation

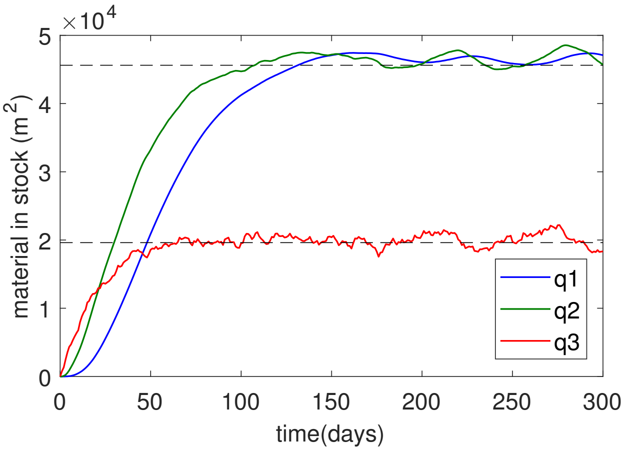

Figure 6: Initial building of WIP - DES simulation

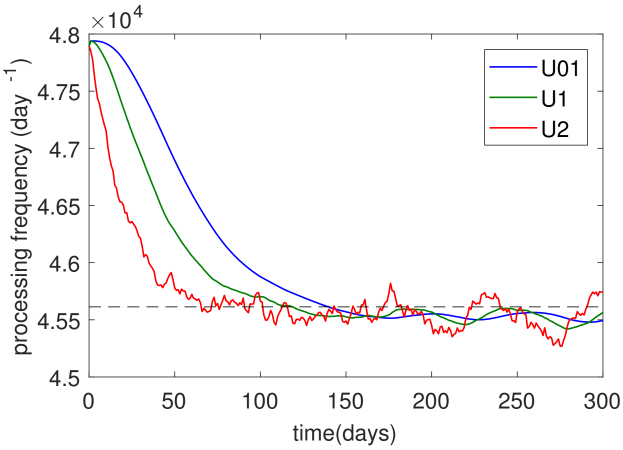

Figure 7: Adjustments of processing frequencies and material input flow - DES simulation

Figure 5 shows the main part of the simulation scheme. The manufacturing system is modelled as a series of three queue-server pairs, each representing a workstation in the system with the accompanying input buffer. Entities in the model represent a fixed quantity of product (*unit_size* parameter) expressed in m^2. A path splitting element is inserted in between workstations 2 and 3, which models the division of material flow. Entities are routed through the split based on result of the *PortSel()* function, which is programmed to act randomly but also to maintain prescribed values of average material flow through the split output ports. In particular, the average flow through port 2 must correspond to 43% of the total flow.

WIP levels in the system directly correspond to the number of waiting entities in queues. These are used as feedback signals to the controllers. Controller outputs U_i represent input material flow to workstation 1, and processing frequencies of workstations 1 and 2, respectively. Input material flow requirement is translated into the intergeneration time of the *Entity Generator*, while processing frequencies are transformed into service time of the related *Entity Servers*. This way the production control loop is closed within the simulation model. *Memory* blocks are inserted in feedback paths to break the algebraic loops.

Figures 6 and 7 illustrate how the controller builds the required WIP levels when starting from empty buffers and using DES model. The stochastic behaviour in the shown result is mainly induced by the implementation of the material flow splitting in DES, which is based on specified discrete distribution of random values.

This is closer to operation of the actual system, where the material flow is not necessarily continuous in between production orders. Each product family includes different products, and machine setup is needed in between production of different products, i.e. before executing the production orders. The actual material flow in a given moment depends on the actual production orders prescribed by master production schedule (MPS), detailed operation scheduling, standstills and other disturbances etc.

Therefore the product mix percentage only represents average values, the actual daily quantities of product families vary during the manufacturing operation.

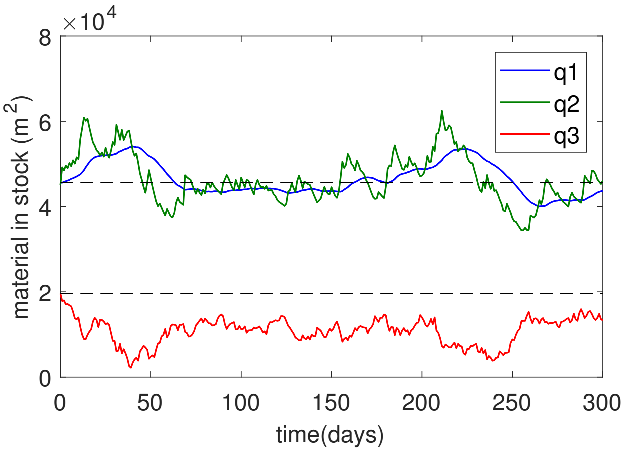

Figure 8: WIP levels in the presence of disturbances - machine breakdowns

Similarly, other random effects could be explored, such as nondeterministic processing frequencies of the workstations etc. E.g., instead of simulating complete workstation 2 breakdown, Figures 8 and 9 illustrate WIP levels and related adjustments of processing frequencies when occasional machine breakdowns occur within workstation 2. Note that workstation 2 consists of 12 parallel looms and simulated scenario assumes exponentially distributed breakdown times of a single loom with average rate of 1/2 day and uniformly distributed repair times in the interval (0,1). Figure 10 shows machine breakdown times where value 1 indicates single machine breakdown and value 2 simultaneous breakdown of 2 machines.
Comparing Figure 6 and Figure 8, it is possible to see that the WIP levels of buffers 1 and 2 present oscillations with a little bit higher amplitude (and present also high-frequency oscillations, in the case of buffer 2). Nonetheless, the results show that, even in the presence of these disturbances, the WIP levels of buffers 1 and 2 remain around the reference values. This indicates that the defined control strategy for the source of flow and for the workstation 1 remains effective in the presence of disturbances. For the buffer 3, an expected offset is observed, since the workstation 2 had its capacity reduced. In addition, it may be noted that the controller tries to compensate the machine breakdowns by increasing the processing frequency of workstation 2 (Figure 9). This means that the remaining parallel machines of this workstation would have to work faster or for longer times (i.e. to do overtime) in order to compensate the downtimes of the temporarily broken machines. These expected results shown that the continuous model and the discrete model are coherent.
The continuous formulation is suitable for this manufacturing system presented in previous works since the manufactured products are continuous until they reach the cutting operation (i.e. the final products are based on a continuous tubular fabric, in this case). However, the representation of the system as a discrete model is a relevant step towards its application in a much broader range of cases, where the products are measured in discrete units. Even if the product quantity is measured continuously,

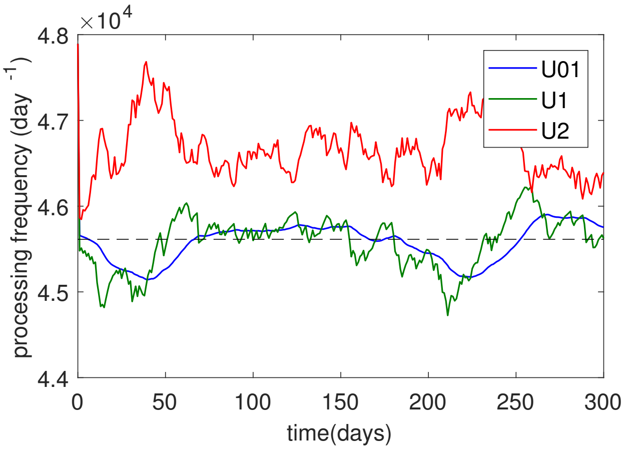

Figure 9: Adjustments of processing frequencies and material input flow in the presence of disturbances - machine breakdowns

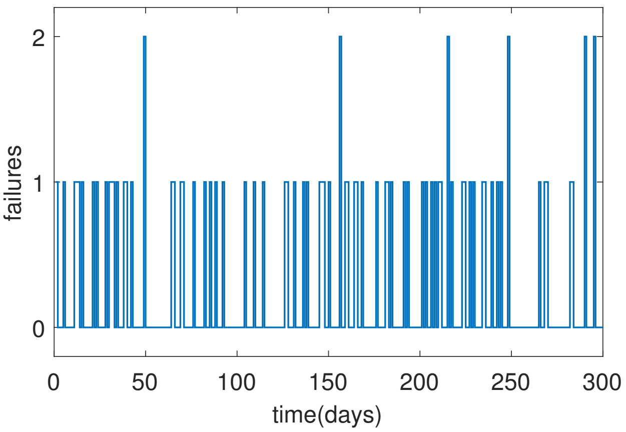

Figure 10: Machine breakdowns

such as in the given case, it makes sense to verify how the controller designed for the aggregated continuous model deals with non-ideal and discontinuous material flow situations that are present in reality. On the other hand, building exact simulation model that would exhibit all the specifics of the given manufacturing system is often too difficult.
In addition, the capacity adjustments prescribed by the controller do not correspond, in practice, to a direct increase or decrease in the production rate of a given machine, since this rate is subjected to technological constraints and can only vary within a specific range, as known. Rather, these capacity adjustments may be converted into an indication of downtime or overtime of the machines. In other words, if the controller prescribes that the capacity must be increased in 20%, it does not mean increasing the production rate in 20%, because this is usually infeasible. In practical terms, this adjustment has to be implemented by means of overtime or an extra shift, for instance, and the representation of the system as a discrete model allows to include and test these more realistic conditions.
Unfortunately, it can be shown that chosen control strategy does not cope well with larger disturbances in the

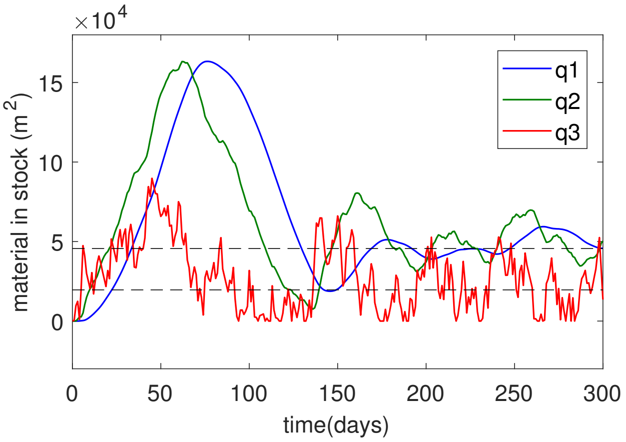

Figure 11: DES simulation considering lot sizes

material flow. Figure 11 shows the results of WIP level control when material flow splitting is not smooth but considers lot sizes. A product dependent lot size of material goes through the same path over the manufacturing system. In case of larger lots this substantially disturbs the flow balance and represents a challenge for the WIP level controller. As a result, large overshoot is present in the initial WIP building phase and oscillations around required WIP levels remain present after the required buffer levels are reached. Additionally, integrator state limitations had to be relaxed in order to avoid steady state error (offset) of WIP levels. The improvement of the control strategy remains one of the issues for the further research work, especially when considering lot sizes.

6. CONCLUSIONS

The verification of the production control strategies indicates that the developed continuous model adequately represents the production system dynamics and is useful for development of production control strategies. In comparison to the controlled DES model, the simulation with continuous model is computationally more efficient and therefore much more appropriate for controller tuning. Verification of the control strategy in DES setting is advantageous in the sense of more realistic testing scenarios that can be easily implemented. It therefore presents a useful stage in verification of production control strategies.

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