Advances in Simulation for
Production and Logistics Applications
Markus Rabe (ed.)
Stuttgart, Fraunhofer IRB Verlag 2008

Use of Simulation for Improving the Output Rate: An Industrial Application

Anwendung der Simulation zur Verbesserung des Durchsatzes: Eine Industrielle Anwendung

Jan Colpaert, Liesje De Boeck,
HUBrussel, Brussels (Belgium)
Inneke Van Nieuwenhuyse, K.U.Leuven, Leuven (Belgium)

Abstract: Our research focuses on improving the output rate of a single product CONWIP system. The system has zero intermediate buffer capacity but may use time buffers which result from minimum and maximum processing times on each workstation. The transport between the different workstations is accomplished by a single resource (a bridge crane), constituting the bottleneck of the system. Since no mathematical approach exists to model this problem, we use simulation. To determine the parameters for the simulation scenarios, we rely on CONWIP, queueing and Factory Physics® literature. We apply the model to an industrial case. The results reveal major improvements in the output rate. The decision framework used, appears to be valuable for other real-life performance improvement applications based on simulation. The results also generate generic insights in improving production performance in similar systems.

1 Introduction

Real-life problems frequently offer interesting research questions. In the ideal case, a generic mathematical model can be developed in reply to the research question and comparable research questions. In many cases however, the problem complexity is such that simulation is the only alternative (Law and Kelton 2000). As a result, the model itself tends to be less generic since it is rather custom-made.

The real-life study, aiming at improving the production output rate in the paint department of a Belgian industrial company, belongs to the second category. The real-life system can be considered as a single product CONWIP system (for a definition of a CONWIP system, we refer to section 2) with zero intermediate buffer capacity and time buffers. A single bottleneck resource is used as transportation device for the jobs between the different workstations. Since, to the best of our knowledge, no mathematical model exists to solve this problem, we will rely on simulation. Three industrial advantages can be gained from the study:

1. we develop a framework in preparation for the simulation model which can be valuable for other real-life performance improvement applications based on simulation,
2. we get a company-specific gain by improving the company's production output rate,
3. we derive insights in general production behavior which fit within the existing CONWIP (Framinan et al. 2003) and Factory Physics® literature (Hopp and Spearman 2000).

Given these advantages, we can define our contribution related to the existing literature as follows. As the part of the paint department behaves as a CONWIP system (see section 3), we refer to Framinan et al. (2003) who provide a good state-of-the art overview of the CONWIP literature. They classify the existing literature on CONWIP systems in contributions related to the operation of CONWIP systems, the application of CONWIP systems and the comparison with other production control systems. Our paper adds to the application of CONWIP systems (for which the literature is very scarce) by providing a solution for a real-life problem. By analysing the system by simulation, we gain additional insights in single product CONWIP systems with zero intermediate buffer capacity and time buffers operating under a single bottleneck resource. By then confronting simulation input and output, generic insights concerning factory performance can be derived, adding to the Factory Physics® literature (Hopp and Spearman 2000).

The paper is organized as follows. In the second section, we zoom in on the system characteristics in order to constitute a decision framework including research questions and methodology. In the third section, we elaborate on the industrial application and the related models and results. In the last section, we summarize the most important conclusions and insights of this study.

2 Decision Framework

Before focusing on the decision framework of our real-life study, we represent in figure 1 a general decision framework. This framework can be viewed as a 'standardization' of the ideas advocated by Hopp and Spearman (2000) and Standridge (2004). This framework can be used for general real-life factory performance improvement studies using simulation. We then specify this framework in terms of our real-life study.

Our real-life system is a single product CONWIP system (see Hopp and Spearman (2000) for a detailed analysis of a general CONWIP system). Note that Spearman et al. (1990) were the first ones reporting on a CONWIP system. In general, we can define a CONWIP system as a system where the work-in-process (the number of jobs present in the system) is held constant by allowing a new job into the system at the moment another job leaves the system (Framinan et al. 2001). The system has zero intermediate buffer capacity. All workstations in the CONWIP system have their own minimum processing time and their own maximum processing time. As such, each workstation has a kind of time buffer: if the next workstation has not yet finished processing and/or the transportation resource is not available, a job can stay for an extra time equal to the maximum processing time minus the minimum processing time at its current workstation. The workstations can only hold one job at the time. The transport between the different workstations is accomplished by a transportation resource. This resource is limited in capacity and constitutes the bottleneck of the system.

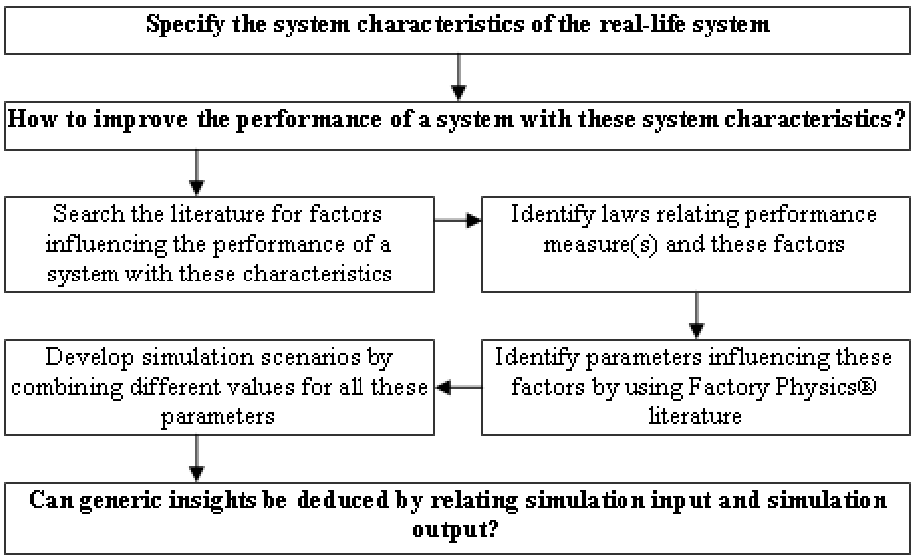

***Figure 1**: Decision Framework*

Given that we want to improve the output rate of this system, our *first research question* can be stated as: how can the output rate (the number of jobs leaving the system per time unit) be improved in this type of CONWIP system? Note that the time buffers and the bottleneck transportation resource seriously complicate the system setting. That is probably the reason why we did not find any analytical model in the related literature capable of modelling the output rate of such a system. Consequently, we will use simulation. Note that Framinan et al. (2003) also report on simulation to study CONWIP systems next to analytical models and a hybrid combination of analytical and simulation models. Along the same lines, Law and Kelton (2000) report on simulation models as an alternative when no analytical models exist. To improve the output rate in this type of CONWIP system, we will focus primarily on setting the CONWIP-level and influencing job sequencing, because these are the most frequently used factors to influence system performance in a CONWIP system (Framinan et al. 2003): setting the CONWIP-level relates to determining the average work-in-process (WIP, the average number of jobs present in the system) and job sequencing relates to influencing the average cycle time (CT, the average total time it takes a job to traverse the system).

Since Little's law (Little 1961) specifies a general relation between output rate (also defined as throughput (TH) in what follows), WIP and CT, we will use this law to proceed in finding the relevant parameters for our simulation study. The usefulness of analytical laws for the design and evaluation of simulation experiments has been discussed previously in Standridge (2004). Little's law states that WIP equals TH times CT (on the long run). This law clearly reveals that we can play with WIP and/or CT to influence TH. Next, we need a translation in terms of parameters we can play with to affect WIP and CT. For this purpose, we will rely mainly on the existing Factory Physics® literature (Hopp and Spearman 2000). Based on a combination of these specific parameters, we will develop the simulation scenarios in what follows. A first factor which can affect the output rate in a positive way is *increasing WIP-level*. However, an *increase in WIP-level* may lead to a higher utilization of the transportation resource and/or increased blocking occurrences (jobs are blocked in a workstation since the next workstation is busy and/or the transportation resource is not available for transport to the next workstation). This may imply a CT increase which is higher than the increase in WIP-level, thus lowering the output rate. The WIP-level increase should therefore always be relatively higher than the induced CT increase. Note that WIP and CT (for a fixed TH) are equivalent parameters (Li et al. 2007) but measured in different units (Hopp and Spearman 2000). A second factor which can influence the output rate is CT. By *decreasing CT* (keeping the same WIP-level), the output rate will increase. By playing with the *queue discipline* (i.e. the priority rules used to determine which jobs to move to their next workstation if more than one job needs the transportation resource for its transport to the next workstation), we can influence CT. Note that the existing queueing literature reveals that the queue discipline is indeed a determining parameter in CT calculations and performance in general (see e.g. Dupon et al. 2002; Maertens et al. 2008). Another way to change CT is to experiment with the *coupling/decoupling mechanism of the transportation resource*. When coupling is used, the transportation resource waits at the workstation till the job has finished its processing in that workstation; when decoupling is used, the transportation resource becomes available for performing other tasks. By coupling the transportation resource, we make it less flexible, in this way degrading performance. In general, flexibility with respect to resources, production lines, etc. has a positive impact on performance (see e.g. Jordan and Graves 1995; Hopp and Spearman 2000). We can also *introduce artificial waiting time* to influence CT. This means that we force a job to stay longer at the workstation than its minimum processing time. Note that the artificial waiting time used for a specific workstation depends on the difference between the maximum and the minimum processing time on that workstation. As a result, we change the moment at which jobs request service from the transportation device. Although this forced waiting time obviously will lead to an increase in CT, the 'natural' waiting time may decrease as a result of the change in requests for service (i.e. a change in arrival pattern) for the transportation device. Indeed, the resulting arrival pattern may become less variable in this way improving performance (see e.g. Li et al. 2007). Remark that Hopp and Spearman (2000) state that variability always degrades performance. The last (and most obvious) option to affect CT is *increasing capacity*. This may be accomplished by providing extra resources (workstations and/or transportation resources). Note that increasing capacity for highly utilized resources can lead to a substantial reduction in CT (Hopp and Spearman 2000).

Related to this first question is the *second research question*: can generic insights be derived from this CONWIP setting by relating simulation input with simulation output? Since the time buffers in the CONWIP system are a rarity, insights will relate to this system characteristic.

3 Industrial Application

The real-life study is performed in a company manufacturing cold-rolled steel profiles. The manufacturing takes place in three successive departments (the production, the paint and the finishing department). We note here that jobs need not necessarily be processed in each department and that the departments may be considered as being disconnected. The problem the company is confronted with is located in the paint department and more specifically in one part of this department, i.e. the series of baths. This part is the bottleneck of the paint department, delaying the product flow in this department. To be more precise, it is the bridge crane, used as transport device in the series of baths, which is the bottleneck.

If we zoom in on the company's production framework, we get figure 2. A detailed description of the parts of interest in figure 2 is given in subsection 3.1.

3.1 Detailed Processing of Paint Department and Series of Baths

In the paint department, the steel profiles receive a protection layer to prevent them from corrosion and damage. This starts in the first workstation by manually loading the profiles on racks. They then move to the series of baths were they are immersed in different baths to receive a protection layer. This layer is fixated by heating the profiles in an oven. Next, the profiles receive a powder coating which is fixated in the powder oven. Finally, the profiles are unloaded from the racks.

In the series of baths, the racks are moved individually to the input/output position (I/O position) by a conveyor. The transport of the racks between this I/O position and the baths and between the baths is accomplished by a bridge crane. The conveyor however moves the racks one by one, whereas the bridge crane handles the racks in pairs. This results in the need to form rack pairs before production in the baths can take place and to split rack pairs before transportation to the next workstation in the paint department. The standby position is needed in forming and splitting the rack pairs since the I/O position can only hold one rack at the time. The bridge crane can move horizontally along the baths and can take three vertical positions above the baths. Position 1 is the highest position used to transport the rack pairs between the baths. The lowest position (position 3) enables immersion of the rack pairs in the baths or moving the bridge crane between baths when it does not contain a rack pair. Position 2 is the middle position used to drain the rack pairs above the baths. After a rack pair has been immersed in a specific bath (note that a bath can only hold one rack pair a time), the bridge crane can remain coupled to a rack pair or can be decoupled. In total, there are four profile types. Each type has its own deterministic routing through the baths (depending on the type of protection layer desired). Production only takes place for one type of profiles at the same time. The processing time in each of the baths is bounded between a bath specific minimum (MIN) and a bath specific maximum value (MAX).

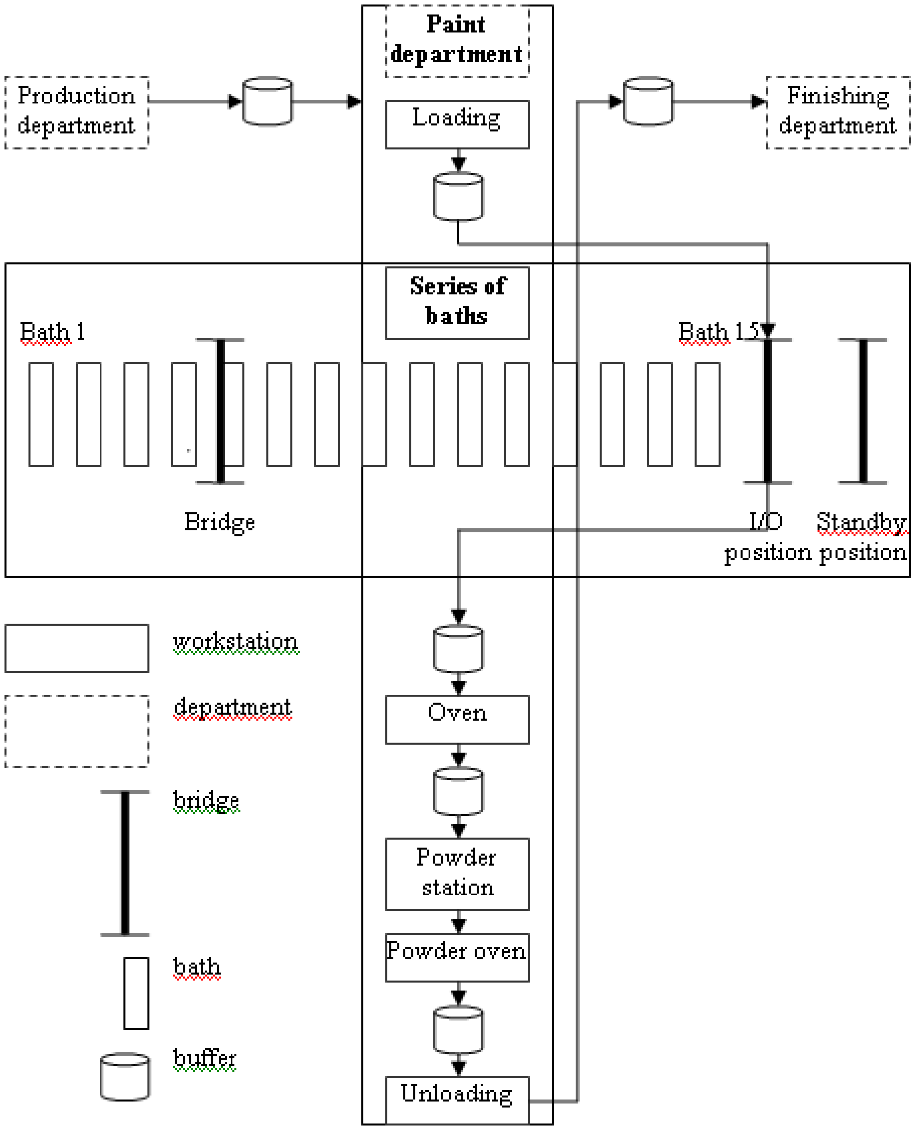

Figure 2*: Production Framework*

The racks should stay for at least MIN time units (to get the desired protection layer) in a bath and for at most MAX time units (otherwise, the profile must be considered as scrap). At the end of the routing, the bridge crane moves the rack pairs back to the conveyor where they are split and transported to the oven. Only at that moment, a new rack pair may enter the series of baths. This means that when it is decided to fill up the series of baths with two rack pairs, the WIP in this series of baths will always remain at a level of two rack pairs.

To conclude this subsection, we note that since the bridge crane is the only active resource in the series of baths, improving the output rate boils down to determining the optimal sequence of bridge crane movements.

3.2 Models and Results

In the previous section, we derived five different input parameters in forming our simulation scenario's (WIP-level, queue discipline, coupling/decoupling mechanism of the transportation resource, introducing artificial waiting time and capacity increase). We now translate these parameters into different values for our real-life system:

1. WIP-level: two (number in the current setting) and three rack pairs (note that the number of rack pairs present in the series of baths for a specific profile type is limited to the number of baths used in the routing of that profile type; however, a WIP-level of four rack pairs for each profile type appears infeasible as it causes a violation of the maximum processing time constraints),
2. queue discipline: FIFO, priority to the bath with the longest processing time, priority to the bath with the highest bath number and priority to the bath with the lowest bath number,
3. coupling/decoupling mechanism of the transportation resource: all combinations of coupling/decoupling the bridge crane, for all baths,
4. introducing artificial waiting time: we introduce different possibilities for the timing of requests for service for each bath (minimum bath processing time + 0, 1/3, 2/3 and 3/3 of the bath's buffer 'capacity'), and then combine all possibilities,
5. capacity increase: we add a second bridge crane (increasing capacity by adding one or more baths is financially not feasible).

To limit the number of simulation scenarios, we first combined all values for the first four parameters in a first step. For each scenario of each sequence, we performed one simulation run with a length of 50 hours. We note here that as all scenarios generated a 'deterministic output' (there is a cycle determining a sequence of bridge crane movements which is 'infinitely' repeated), one single run is sufficient to judge the performance of a scenario. In a second step, we used the best values for the first three input parameters (WIP-level: three racks pairs, queue discipline: FIFO and bridge crane decoupled for all baths) and all combinations for the fourth parameter to test the scenarios with an additional bridge crane. Note however that at this point, an additional difficulty comes into play. Knowing that the second bridge crane may cover baths 1 till 13 and the first bridge crane baths 3 till 15, we should make a choice of which bridge crane to request. Indeed, baths 3-13 are covered by both bridge cranes. We here assume five possibilities: b10, b11, b12, b13 and b14 where bx means that the first bridge crane takes on baths x till 15 and the second bridge crane baths 1 till (x-1). Also here we performed one simulation run with a length of 50 hours for each scenario of each sequence.

Comparing all scenarios in terms of the output rate, then reveals which is the best scenario. Note that simulation does not give the optimal solution (it only provides the best result for all simulation scenarios). However, in order to get a feeling of how far we are from the optimum result, we may again use Little's law. Knowing that this law states that WIP equals TH times CT, we reach maximum throughput (for a given WIP-level) when cycle time is minimal. The minimum cycle time of a rack pair in the series of baths is known, as it is the time needed to go through all workstations without any waiting in between (it equals the sum of: the time to move the rack pair between the I/O position and the baths (and vice versa), the time to move the rack pair between successive baths in the sequence, the time to move the bridge crane(s) along the necessary vertical positions to immerse and drain the rack pair, the minimum processing time in the baths and the drain time above the baths). Hence, we know the upper bound on TH for every WIP-level.

We plot the results for all four profile types in figure 3 (each profile type is plotted on an axis). The plotted results (TH in racks per hour) are the best results obtained from all scenarios in the indicated categories and not violating the maximum processing time constraints: TH with WIP-level=3 (rack pairs), without capacity increase (first step) and TH with WIP-level=3 (rack pairs), with capacity increase (second step). To be able to judge these results, we also indicate the current TH of the series of baths as well as the maximum achievable TH (given a WIP-level equal to three rack pairs).

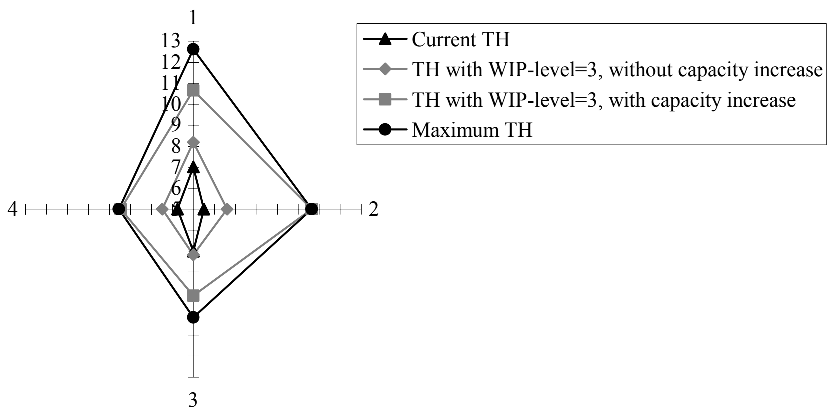

***Figure 3**: Results for the Output Rate of each Profile Type for Different Categories*

We clearly observe from figure 3 that a capacity increase is necessary to substantially (close to maximum TH) improve the output rate in the series of baths. Indeed, in the single bridge crane scenarios (category 'TH with WIP-level=3, without capacity increase') output rate improvement (compared to the current case) is very small. The reason is the high bridge crane utilization, preventing major improvements in the current system performance. The simulation results show that the bridge crane utilization amounts to more than 90% for all sequences, indicating that the bridge crane forms the bottleneck and that there is little room for further improvement. However, interesting to note is that, although small, the improvements in this category are made in scenarios where the artificial waiting time is introduced. As such, exploiting time buffers may yield some improvement. This is not surprising since it may lead to lower inter-arrival time variability for the transportation resource. Lowering variability always improves performance (Hopp and Spearman 2000). Note also that this variability decrease has a significant impact when utilization is rather high (90% or higher). That is the reason why in the scenarios with two bridge cranes (the bridge cranes here have a substantially lower utilization), the impact is lower. So in general we can state that exploiting time buffers can improve system performance if it lowers the variability in the arrival pattern at the different resources.

To conclude this section, we briefly note that further analysis revealed that the throughput improvements could be secured in the whole paint department with only some minor investments at the other workstations. Moreover, the marketing department of the company is confident that market demand is high enough to fully absorb the increased output from the paint department. Hence, the company decided to make the necessary investments in order to implement the recommendations of our study in practice.

4 Conclusions

In this paper we carried out a real-life simulation study for a Belgian industrial company manufacturing cold-rolled steel profiles. The problem the company is confronted with is located in the paint department where profiles receive an additional protection layer to prevent them from corrosion and damage. The series of baths, and more specifically the bridge crane which is used as transportation device between the baths, is the bottleneck of the paint department, delaying the product flow throughout this department. Improving the output rate of this process is the main goal of this study. The study revealed three contributions.

First, we developed a decision framework in preparation of the simulation model which can be valuable for other real-life factory performance improvement applications by means of simulation. The framework starts by listing the system-specific characteristics. Here, the series of baths functioned as a single product CONWIP system with zero intermediate buffer capacity, time buffers and a bottleneck transportation resource. The first research question then asks how to improve performance of a system with these system characteristics. In answering this question, we first search the existing literature for factors influencing the performance of a system with these characteristics and laws relating performance measure(s) with these factors. Then we rely on Factory Physics® literature to identify parameters affecting these factors, followed by combining the different values for these parameters to develop the simulation scenarios. By now confronting simulation input and output, generic insights may be derived.

Secondly, we got a company-specific gain by improving the company's production output rate. It turned out that a capacity increase was necessary to substantially improve the output rate in the series of baths, as such approximating the maximum achievable output rate. The high bridge crane utilization in the single bridge crane scenarios prevented major improvement in system performance. In combination with some minor investments in the other stations of the paint department, these improvements can be secured in practice. At the same time the company also guarantees that the market demand is high enough to fully absorb the increased production output.

Thirdly, we derive insights in general production behaviour which fit within the existing literature. We observed that exploiting time buffers can improve system performance if it lowers the variability in the arrival pattern at the different resources.

Finally, we note here that we used simulation since the system is too complex to model analytically. However, since output rate improvement boils down to determining the optimal sequence of bridge crane movement and simulation output turned out to be deterministic, a possible new research direction for this problem type could be the use of models/heuristics in the field of scheduling/sequencing.

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