System Dynamics limits and potentialities in the use of production process simulation

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Abstract: The definition of suitable key performance indicators (KPIs) is essential to control functioning of a production company. Overall Equipment Effectiveness (OEE) proposed by Nakajima in 1988 is one of the most used parameters. However, for example, it is not suitable for analysing production lines, since these usually have decoupling points, and specific rules for the buffer filling could be present. For this reason, new parameters like OEEML, OLE etc. have been proposed over the years, even if simulation approach is an efficient possible option to the analytical one: discrete event simulation and System Dynamics (SD) are the most used simulation kinds. This latter, in particular, is typically used in strategic and distribution processes, characterized by a high complexity level. This paper, instead, presents the possibility of using System Dynamics simulation for analysing the performance of a production process. For this reason, a pharmaceutical packaging line has been modelled in Analytica (a SD simulation software), then verification and validation of the simulation model has been done. Some of the most significant parameters of the line have been analysed in order to verify the suitability of the considered approach.

Keywords: System Dynamics, simulation, packaging line, performance evaluation

1. Introduction

The definition of suitable key performance indicators (KPIs) is essential to control the functioning of a production company. There are, in fact, many common kinds of losses in a production processes. Seiichi Nakajima, in his prominent works, classified production losses in three main categories (availability, effectiveness and quality losses) introducing the Overall Equipment Effectiveness (OEE) indicator (Nakajima, 1988). This tool became increasingly popular over the years, and is one of the most used quantitative metrics for evaluating the effectiveness of a production machine in a manufacturing system. However, its use is suitable only for a single equipment, as highlighted by many authors (Nachiappan and Anantharaman, 2006) (Huang et al., 2003). At the same time, it is obvious that very few machines run isolated and without interactions with others: in a production line, each workstation is generally deeply linked with the others and the productivity of each one affects the productivity of the others. The arrangement in a production line is one of the possible options to organize a production process. It is proper of a product-oriented system, where products flow from an input point towards the output one in a sequential order. This configuration is very useful when production concerns high volumes.

Since production lines have had a huge diffusion, over the past years others parameters were proposed in order to monitor and improve the performance of the whole production process without considering only a single production station. Overall Line Effectiveness (OLE) (Nachiappan and Anantharaman, 2006), deriving from OEE, for example, was proposed for evaluating the efficiency of a continuous product flow of manufacturing system. This parameter can be used only for a continuous production lines, while is not suitable when buffers are put between machines (Braglia et al., 2008). However, buffers and decoupling points are essential to disconnect operations and to avoid the inefficiencies deriving from fluctuations and variations in productivity (Lutz et al., 1998). For this reason, in (Braglia et al., 2008) a new parameter was proposed: the OEEML (overall equipment effectiveness of a manufacturing line) which allows to have a global parameter of an entire production line.

The packaging process is one of the manufacturing activities that is usually organized as a line: high volumes are involved in a process characterized by several machines with potentially different productivity, where decoupling points are therefore essential. A production of a packaging line could also have specific rules for the buffer filling. In particular, it is possible to have sensors regulating both starting and stopping of buffer filling and the productivity of upstream and downstream machines.

Because of the specific features of production lines in general and of the packaging lines in particular, it is essential to identify the better tools to monitor the performance. Some analytic methods, such as OEE, OLE, OEEML and their derivatives, are usually used to evaluate an overall index. However, in order to have a more complete description of a production process and to consider all the significant elements affecting the line performances, other tools could be valuable. Surely, the simulative approaches are among the most used approaches. There are different kinds of simulation analyses, such as the discrete event simulation and System Dynamics (SD). This latter approach will be briefly presented in section 2.

In this paper we considered a pharmaceutical packaging line analysing the possibility of evaluating its performance through SD simulation. In (De Carlo et al., 2014a) similar analysis for the same packaging line has been already done by the classic OEE and its evolution, and by discrete event simulation: for this reason, in the remainder of this paper, many assumptions derive from that contribution.
The main aim of this paper is to verify the opportunity of using a tool (that is SD simulation) that could be both appropriate to the problem and quite easy to be implemented.
In the remainder of the paper, we have a brief description of System Dynamics (section 2) and of the pharma packaging line implemented in a SD simulation software (section 3). In section 4 the main results are shown; finally, section 5 presents discussions and conclusions.

2. Methodology

As previously mentioned, the analyses presented in this work are based on simulation approaches (in particular on the application of System Dynamics).
Simulation is an important and useful instrument used for new system design and for proposing changes to existing systems facing a change in their operating conditions. One of the most important phase is the definition of a model that could be a proper depiction of the real system. The model is then usually implemented in a software tool; then, after the verification and validation phases, the analyst is ready to analyse several scenarios and the effects of hypothetical changes (Carson and John, 2004).
In the present paper, we will deal with System Dynamics (SD): it is an interesting alternative to the widespread discrete event simulation, specific for complex systems such as social, managerial and economics systems. According to Jahangirian et al. (Jahangirian et al., 2010), for manufacturing and business projects, SD is the second most applied simulation technique. Furthermore, its adoption regards different kind of industries, like automotive, pharmaceutical, utility companies, service industries (Jahangirian et al., 2010). SD, in fact, applies to problems involving changes over time (dynamic problems) (Richardson, 1991) through stocks, flows, feedback information loops and delays.
A simulation based on SD consists of three important elements. The first one is the definition of feedback loops. A feedback loop exists when information resulting from actions in the process, cause a change in the original state of the system, potentially influencing future actions (Figure 1): for example, a problem leads to actions producing results that create future problems and actions (Sterman, 2001). Obviously, this structure has no beginning or end.

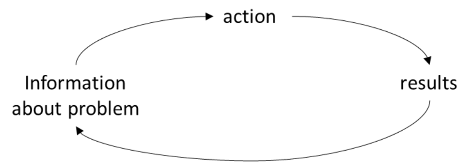

Figure 1: representation of a general causal loop diagram

Each system could be defined through one or more feedback processes. They can be positive (or self-reinforcing loops and negative (or self-correcting) loops. A positive loop tends to reinforce the current evolution of the system, while a negative loop effects in a contrary mode.

The second element regards the identification of stock or accumulation variables (levels) and their inflows and outflows (rates). A stock is the level of an entity in the system, while the rate defines reduction and increase of the level itself. Level usually refers to the resources of the system, which are both tangible and intangible elements (Sterman, 2001). Therefore, stocks and flows define the accumulation and the dispersal of resources of the system.
In Figure 2 we have a general stock and flow diagram with feedback loops too.

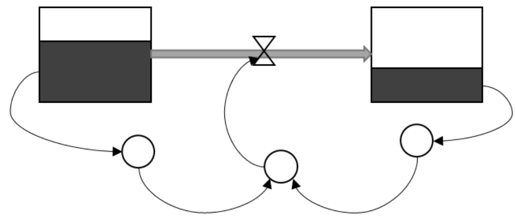

Figure 2: representation of a general stock and flow diagram (with feedback loops)

The third element characterizing SD simulation is the time delay between taking a decision and its effects on the state of the system (Sterman, 2001). It has an important effect on the behaviour of the whole system since delays in feedback loops cause a greater instability.

The models just defined are usually built and simulated using some computer software. In our case we used Analytica (developed by Lumina Decision Software). It has a top-level diagram window, which is an end-user interface summarizing the most important parameters of the model. This top-level diagram has some buttons for displaying the variable values, while another one shows an influence diagram. The influence diagram is a graphical representation of the model showing the defined variables (represented by nodes) with the related interactions (represented by arrows) and the main modules of the model. In fact, in a model we might have different variable types (each one with a different shape), such as general variable, decision variable, chance variable, objective variable. Modules, represented by a thick-lined rounded rectangle, define the details of a specific part of the model.
In a nutshell, Analytica is quite easy to use.

3. Implementation of a pharmaceutical packaging line in the SD Analytica software

As said before, the case study is a pharmaceutical packaging line, modelled through a System Dynamic simulation. The line architecture is quite complex but, to simplify the analysis, only a small part of this line was implemented in the Analytica software. In particular, in this model we considered only the bottleneck of the line, its upstream station and the included buffers (Figure 3) since this is the most critical part of the whole line. A more detailed description of the line is in (De Carlo et al., 2014b).

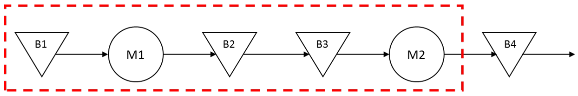

Figure 3: The part of the pharma packaging line implemented in Analytica

Briefly, B1 is the buffer in which phials (the product flowing in the packaging line) await for the first machine M1 (labeller). After the labelling station, phials flow in the buffer B2 that is a crossing point for the real buffer B3. This latter is a vibrating belt and its speed depends on some logics activated by particular sensors.
In Figure 4, we have represented the influence diagram obtained by the implementation in Analytica software of the process line of Figure 3. The interactions between the modules of the model are clearly shown.

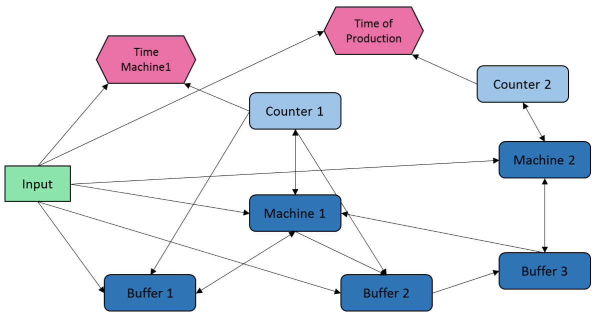

Figure 4: Influence diagram of the line implemented in Analytica

The different shapes and colours of the modules in Figure 4 mean that each one of them has a specific function in the simulation model:

- The objective variables (*Time Machine 1* and *Time of Production*) are KPI of the models;
- The decision variable (*Input*) is a variable under the direct control of the analyst;
- The general variables (*Counter 1* and *Counter 2*) define other quantities of the problem;
- The modules (*Machine 1*, *Machine 2*, *Buffer 1*, *Buffer 2* and *Buffer 3*) have other modules and variables inside.

Each element of the real packaging line is then modelled through variables interaction. Here we will describe only some modules for example

3.1 The Machine 1 module

This module defines the labeller machine operation; it has five variables inside (Figure 5).

- *Machine 1* defines the output of the labeller machine;
- *Prod_M1* represents the Machine 1 productivity at operating speed;
- *Rel_M1* defines the reliability of Machine 1;

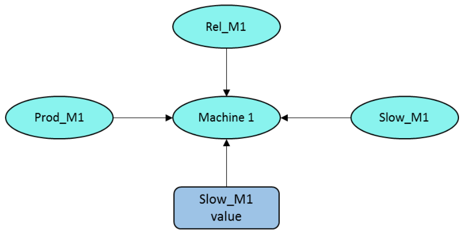

Figure 5: Diagram defining Machine 1

- *Slow_M1 value* is a general variable for the number of phials defining a condition of reduced productivity for Machine 1.
- *Slow_M1* defines productivity of Machine 1 at the end and beginning of a batch.

3.2 The Buffer 3 module

This module represents the vibrating belt of the pharma packaging line. In Figure 6, we have the variables defining the Buffer 3 module.

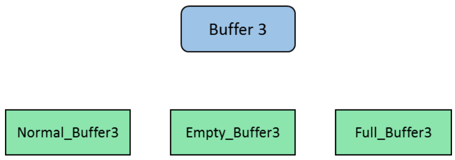

Figure 6: Diagram defining Buffer 3

- *Buffer 3* is the general variable counting the amount of phials on the vibrating belt;
- *Empty_Buffer 3* defines the number of phials on the vibrating belt causing the stop of Machine 2;
- *Full_Buffer 3* defines the number of phials on the vibrating belt causing the stop of Machine 1;
- *Normal_Buffer 3* is the number of phials in Buffer 3 causing the re-start of Machine 2.

All the logics regulating start and stop of Machine 1 and Machine 2, as said before, are explained in another paper of the authors.

4. Verification and validation of the simulation model: main results of the SD simulation model

Verification and validation are two of the most important phases of a simulation analysis. The verification of this model, in particular, was carried out during the whole model definition phase. The model, in fact, is quite complex: it has a hierarchical structure, many modules are interrelated and each module has various variables defining the relative operations.

To validate the model we simulated a real batch of 12870 phials. Then, we compared real and simulated results (both values and trends) of the most significant parameters of the line. In the following figures, it is possible to see trend comparisons for Machine 1, Machine 2 and Buffer 3.

Figure 7 refers to Machine 1: the left part regards productivity (pieces produced in each minute) while the right side is for cumulative production; in green the real trend, in blue the simulated one.

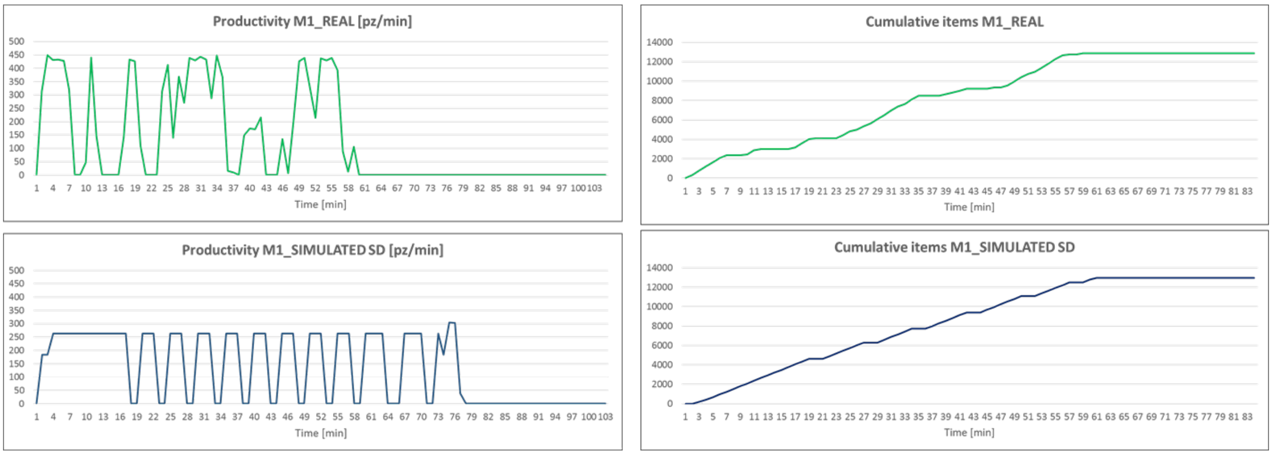

Figure 7: Comparison between real and simulated trend for Machine 1 of the considered batch (12870 phials). On the left side, there is the trend of productivity while on the right side there is the trend of cumulative production.

Analysing Figure 7 it is possible to see that trend of the simulated curve (both productivity and cumulative production) does not exactly reflect the real one: in particular, there are less stops than in the real case (the production stop corresponds to a constant line). Machine 1, in fact, in the SD simulation model, comes to a stop only when a blocking condition occurs (Buffer 3 is too full), while it is not possible to model the reliability problems.

While the real productivity of Machine 1 (top of the figure) has discontinuities related both to blocking condition and to other production stops (reliability, quality, braking problems), the simulated curve has stops only for blocking condition. On the other side, productivity in the simulated scenario has almost a constant value while the reduction at minutes 59-61 derives from the condition of reduced productivity (end of the batch).

Figure 8 shows real and simulated trends for Machine2. What we have outlined for Machine 1 is also true for Machine 2. For this station it is important to say that differences between real trend and simulated one depend also on the choice of simulating only a specific part of the real packaging line (as highlighted in Figure 3): the SD simulation model analysed here does not convey the problems downstream of Machine 2.

Finally, Figure 9 shows the number of phials in Buffer 3 both in the real and in the simulated case. As said before, this buffer is regulated by some logics causing stops and restarts of Machine 1 and Machine 2. In Analytica software, these are implemented as explained in section 3.2. The peculiar saw tooth shape of filling and discharge of Buffer 3, is quite clear in the simulated case: this means that both the “too full” and the “too empty” conditions are verified. Similar analyses have been done for Buffer 1 and Buffer 2, and similar are the related findings, too.

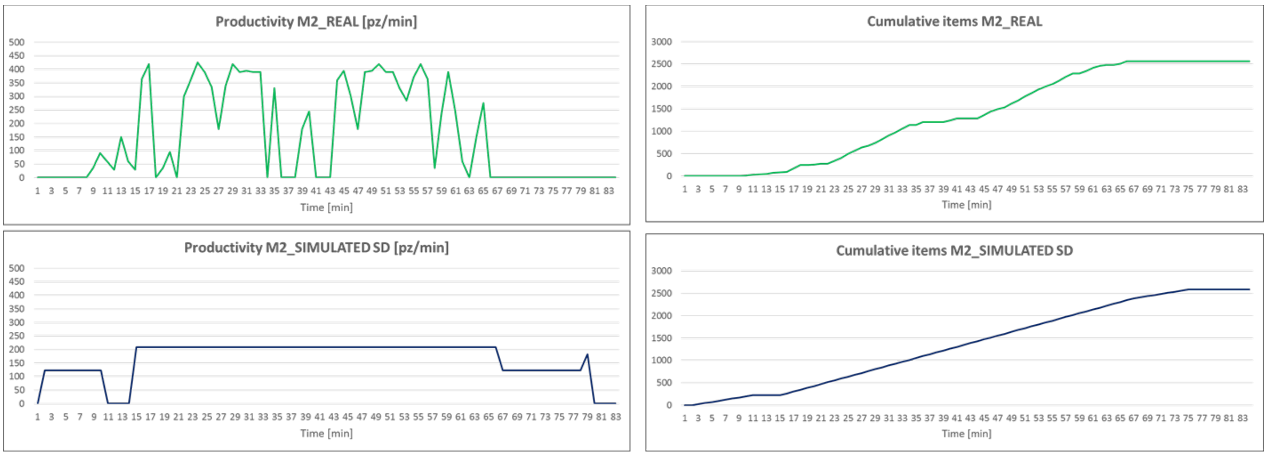

Figure 8: Comparison between real and simulated trend for Machine 2 of the considered batch (12870 phials). On the left side, there is the trend of productivity while on the right side there is the trend of cumulative production

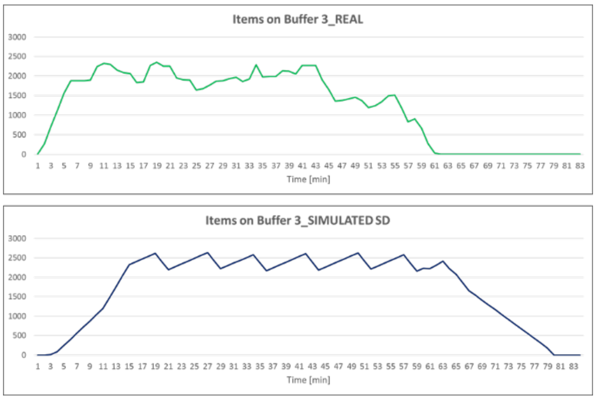

Figure 9: Real vs. simulated number of pieces in Buffer 3 (the vibrating belt)

5. Discussion and conclusion

The validation phase described in section 4 allows verifying the possibility of using System Dynamic simulation for the evaluation of production process performances. In particular, comparing the most significant quantities of the production process (real vs. simulated) it is possible to identify advantages and disadvantages related to the use of SD.

System Dynamics simulation model allows to have good qualitative descriptions, rather than quantitative. It correctly represents the behaviour of the machines, but the lack of the stochastic element does not allow the analysis of the interactions between the machines. SD, in fact, considers the expected value of the variables.

This aspect is quite clear considering Figure 7. The simulated productivity for Machine 1 is always equal to the nominal value (433 phials/minute) considering a mean reduction value (for reliability, quality and other possible problems) of 67% (this information derives from real line data analysis; it is an input to the model): the simulated productivity value is equal to 290 phials/minute (433 phials/minute * 67%). Therefore, SD simulation works with "medium value" and, for this reason, does not consider the process randomness. Since the same packaging line was modelled and analyzed through discrete event simulation, it is interesting to compare results of this two kinds of simulation approaches.

According to our experience, SD seems to be simpler than discrete event simulation approach: two analysts with similar expertise required different skills and developing time effort to model the same line. At the same time, SD does not provide detailed information on the simulated process. Nevertheless, you can have a general and strategic direction of the system. While SD considers the expected values of the variables (as highlighted in Figure 7 and Figure 8) discrete event simulation models each event (faults, stops, etc.).

In conclusion, the System Dynamics simulation model could be regarded as a good tool to better understand the operation of the various machines, however without being able to investigate in detail the causes of productivity losses. Another factor to consider is the complexity of the line. Since the analysed packaging line is very complex its modelling through System Dynamics necessarily lead to approximations or simplifications of reality. These could justify the use of a more articulated and onerous software in order to have a more useful and detailed simulation model.

Anyway, System Dynamics seems to be a good approach if we show interest in a quick modelling of process production performances, with a reduced modelling effort.

References

Braglia, M., Frosolini, M., Zammori, F., 2008. Overall equipment effectiveness of a manufacturing line (OEEML): an integrated approach to assess systems performance. J. Manuf. Technol. Manag. 20, 8–29.

Carson, I.I., John, S., 2004. Introduction to modeling and simulation, in: Proceedings of the 36th Conference on Winter Simulation. pp. 9–16.

De Carlo, F., Arleo, M.A., Tucci, M., 2014a. OEE Evaluation of a Paced Assembly Line Through Different Calculation and Simulation Methods: A Case Study in the Pharmaceutical Environment. Int. J. Eng. Bus. Manag. 1. doi:10.5772/59158

De Carlo, F., Arleo, M.A., Tucci, M., 2014b. Pattern Identification in the Buffer Level as a Tool to Identify Inefficiencies in a Pharmaceutical Packaging Line. Int. J. Eng. Bus. Manag. 6.

Huang, S.H., Dismukes, J.P., Shi, J., Su, Q., Razzak, M.A., Bodhale, R., Robinson, D.E., 2003. Manufacturing productivity improvement using effectiveness metrics and simulation analysis. Int. J. Prod. Res. 41, 513–527. doi:10.1080/0020754021000042391

Jahangirian, M., Eldabi, T., Naseer, A., Stergioulas, L.K., Young, T., 2010. Simulation in manufacturing and business: A review. Eur. J. Oper. Res. 203, 1–13.

Lutz, C.M., Roscoe Davis, K., Sun, M., 1998. Determining buffer location and size in production lines using tabu search. Eur. J. Oper. Res. 106, 301–316. doi:10.1016/S0377-2217(97)00276-2

Nachiappan, R.M., Anantharaman, N., 2006. Evaluation of overall line effectiveness (OLE) in a continuous product line manufacturing system. J. Manuf. Technol. Manag. 17, 987–1008. doi:10.1108/17410380610688278

Nakajima, S., 1988. Introduction to TPM: Total Productive Management. Productivity Press Portland, OR.

Richardson, G.P., 1991. System dynamics: Simulation for policy analysis from a feedback perspective, in: Qualitative Simulation Modeling and Analysis. Springer, pp. 144–169.

Sterman, J.D., 2001. System Dynamics Modeling: Tools for Learning in a Complex World. Calif. Manage. Rev. 43, 8–25. doi:10.2307/41166098