USE OF SYSTEM DYNAMICS PARADIGM FOR SIMULATION BASED ANALYSIS OF CYCLE-TIME IN MOULDING INJECTION MANUFACTURING FOR PLASTIC PARTS

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Rezumat. *Analiza ciclului operativ în fabricație furnizează o serie de informații privind durata procesului de fabricație a unui produs finit. Lucrarea își propune să folosească metodologia „system dynamics” pentru diagnosticarea duratei ciclului operativ al unui proces de producție piese prin injecție mase plastice. Informațiile furnizate de acest tip de analiză sunt folosite atât în diagnosticarea proceselor cât şi în testarea şi evaluarea alternativelor de creştere a eficienței fabricației. De asemenea, metodologia propusă poate fi aplicată şi în contextul modelării şi simulării activităților de reproiectare a fluxurilor materiale.*

Abstract. *The analysis of the cycle-time in a manufacturing environment can provide a variety of useful metrics regarding the time required for completing one unite of production. This article aims to use a system dynamics approach to diagnose the cycle-time related to the production process of injection moulding for plastic parts. The clear, unambiguous cycle-time metrics provided by the analysis can help, both in diagnosing process problems, and in testing and evaluating proposed alternatives to improve the production efficiency. Also, the proposed framework can be applied in a variety of modelling contexts, in a process re-engineering or process improvement effort.*

Keywords: cycle-time, analysis, injection moulding, simulation, system dynamics.

1. Introduction

Inherent to the investigation of the manufacturing cycle-time are a set of activities, from defining the optimum production batch, calculations of the quantity of required parts, pre-production steps and production launching, cycle scheduling, management of production activities with current asset engagement, to the analysis and investigation of material flow.

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In scholarly publications that report original empirical and theoretical researches, manufacturing cycle-time was investigated in different approaches [1] developed a mathematical model to determine the common production cycle time for a multi-item production system with discontinuous deliveries and failure in rework [2] concluded in a research related to Lead Time Syndrome (LTS) of Manufacturing Control, that the length of cycle time is correlated with the overall performance of the manufacturing supply chain; previous research shows that a short span cycle time can generate what is known by the field specialists as the bullwhip effect. In an effort to reduce the manufacturing cycle time [3], proposed a methodology based on technical-technological and manufacturing documentation and real production constraints. The authors stipulated that further research should be directed to the analysis and scheduling of manufacturing cycle using software applications from the domain of project management. The System Dynamics modelling and simulation was used to evaluate the effects of the Cellular Manufacturing Process Model (CMPM) on cycle-time and predictability [4]. In CMPM networks of semi-autonomous producer cells (teams) cooperate to produce a complex large-scale system and to reduce cycle-time.

Although one of the main objectives of production management is the reduction of the cycle-time [2], cycle-time metrics provided by the analysis can help both in diagnosing process problems, and in testing and evaluating proposed alternatives to improve the production efficiency.

1.1. **Cycle-time versus lead-time**

In production activities, raw materials or semi-products flow through a series of processes in a succession according to the technological process. CT is used in differentiating total duration of a process from its run time. Summing up the time required to complete each production stage makes up the lead time. Lead time (LT) is the total time required to manufacture an item, including order preparation time, queue time, setup time, run time, move time, inspection time, and put-away time, or simply the elapsed duration between the start and the completion of a process. CT has the biggest ratio in the structure of the production cycle (Figure1), the overall length of which includes the duration of finishing touches as well as time lengths dedicated to the process.

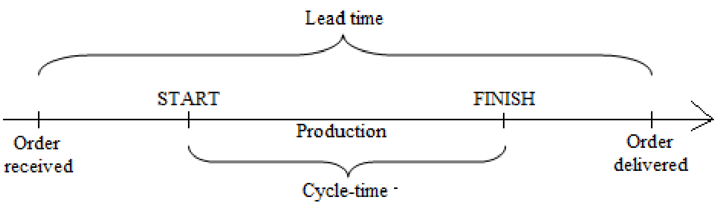

Fig. 1. Difference between Cycle-Time and Lead Time,

Being a quintessential metric used extensively in the operational research of manufacturing processes, CT can be defined as a set of activities which take into account the optimum production lot, amount of required parts, production preparation and kick-off, cycle scheduling, management of assembly activities, also encompassing analysis and investigation of material flows.

2. System Dynamics Approach

Traditionally, issues of manufacturing cycle-time are addressed with software of modelling and simulation in a discrete event or manner. However, when it is desired to analyze manufacturing systems from a holistic perspective, the integration of discrete events in dynamic models proves to be difficult. This article aims to create a framework that could be integrated in System Dynamics modelling and a simulation of a manufacturing cycle-time facing stochastic processes and events.

In opposition with reductionism thinking, system dynamics (SD) deals with systems as a whole, taking into consideration not only the elements which form the system, as well as the interactions between the inner elements, but also considering the interdependencies between the various components of the system by using causal and feedback loops (Figure 2).

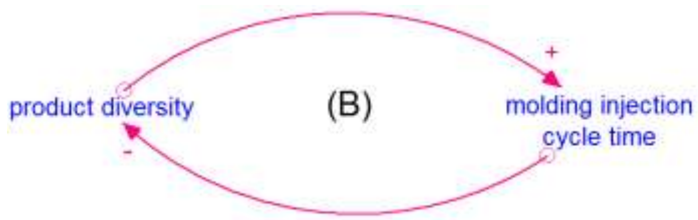

Fig. 2. Balancing Loop:
(+) means the greater product diversity is, the greater moulding injection cycle-time is, while (-) means the smaller moulding injection cycle-time is, the greater the product diversity is.

3. Case Study

In this paper a manufacturing facility that produces injection mould parts is considered. The production facility has 38 injection mould machines, as well as 352 moulds which can be used to manufacture just as many plastic parts, the plant being a Tier 1 supplier, in the supply chain of a refrigerator company (Figure 3). The policy of the company is to ensure a constant stock of finished parts equal to the quantity of parts delivered in two days to the refrigerator factory. This contingency inventory ensures that when an order arrives it can be delivered on the spot. The remaining stock will be depleted by half which in turn is going to generate a new demand of parts from the production department of the enterprise.

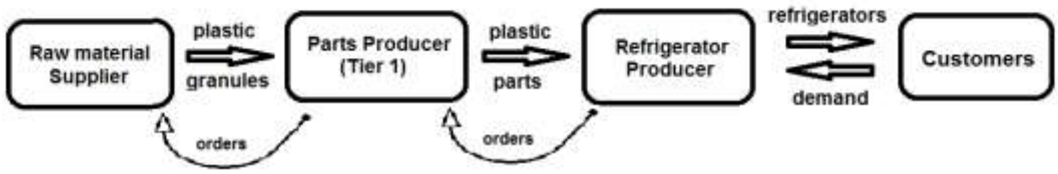

Fig. 3. The focal supply chain.

Injection moulding is a widely used manufacturing procedure employed to obtain various plastic items. This manufacturing process consists of heating up the raw plastic material until it reaches the melting point, after which it is injected under pressure inside a mould, where the rapid cooling process has to take place in order to achieve the solidification of the finished product. Once the applied pressure is lifted, the newly formed material is cooled down and shaped accordingly to the form of the mould, after which it can be removed, thus obtaining the finished product.

Given that the objective of this study is to analyze the cycle-time, a series of measurements have been conducted to assess the time it takes for each critical stage to be completed. Direct observations revealed that the duration of the first critical stage of the manufacturing process, which is the changing of the mould, takes between 15 and 25 mins and depends on the type of mould which is picked for the next product and the type of injection machine, the initial set-up on the technological parameters this change up take up to 10 mins. The injection phase takes up to 60 sec depending on the volume of the part. Another stage which influences in a significant degree the production is a new recalibration of injection parameters that have to be made. These recalibrations are operated 30 mins prior to the commencement of the process (due to the warming injection machine) and it is being repeated every time the ambient temperature modifies. The changes in ambient temperature are influenced by the atmospheric temperature and affect the quality of parts.

3.1. Analytical formulation

The analysis of the methodology of the cycle-time proposed by this article doesn’t focus on one more injection processes but sets the goal of a holistic approach by analyzing the cycle-time for manufacturing a batch of products of a product lot. Thus the main factor that has to be taken into account is the number of parts which have to be manufactured, equal to the factory demand (FD). According to the type of parts that will be produced, a mould is chosen, and depending on the number of nests, which can vary between 1, 4, 6, 8, or 10, (NNM - number of nests in the mould), the number of injection cycles (NIC) is calculated:

$$NIC = \frac{FD}{NNM} . \qquad (1)$$

The next parameter considered is the total duration (TD) for producing the FD, which represents the sum of all durations of injection processes (ICD - injection cycle duration) as well as the duration of the non-value stages like changing moulding duration (CMD), initial setup duration (ISD) and the recalibration duration (RD). A constant factor *k* is considered (based on previous experience) which represents the number of recalibrations to be done, due to ambient temperature changes.

$$TD = (NIC * ICD) + CMD + ISD + (k * RD). \quad (2)$$

Mathematical equation of the TD and NIP results the cycle-time (CT) for the batch production of parts to be replaced in the warehouse:

$$CT = \frac{TD}{NIC}. \quad (3)$$

Percentage of injection cycle from total duration (ICD_TD) of producing a batch is calculated using the equation:

$$ICD\_TD = \frac{NIC * ICD * 100}{TD}\%. \quad (4)$$

Similarly are calculated the percentages of non-value activities from the total duration of producing a batch: changing moulding duration (CMD_TD), initial setup of the technological parameters duration (ISD_TD) and recalibrations setup duration (RD_TD):

$$CMD\_TD = \frac{CMD * 100}{TD}\%. \quad (5)$$

$$ISD\_TD = \frac{ISD * 100}{TD}\%. \quad (6)$$

$$RD\_TD = \frac{k * RD * 100}{TD}\%. \quad (7)$$

The above equations allow further calculation durations of critical stages in relation to CT, and the TD. Therefore, the equation that calculates the changing moulding duration in relation to CT and TD is defined by the relation:

$$CMD\_CT = \frac{CT * CMD\_TD}{100}\%. \quad (5)$$

Similar equations are used to compute the durations of setting parameter stage (ISD_CT) and recalibration of parameters stage (RD_CT) in relation with CT and DT:

$$ISD\_CT = \frac{CT * ISD\_TD}{100}\%. \quad (6)$$

$$RD\_CT = \frac{CT * RD\_TD}{100}\% . \quad (7)$$

Using the same approach as in the equations above, the duration of injection cycle stage is calculated:

$$ICD\_CT = \frac{CT * ICD\_TD}{100}\% . \quad (8)$$

3.2. Modelling and simulating the production cycle-time

The SD model (Figure 4) aims to represent the causal relationships that exist between the parameters that influence the cycle-time. The model has been made with the iThink® software affording stochastic simulations, which is favourable to the conditions under which the duration of CT is defined. The parameters were modelled as converters. The converter pays a utilitarian role in the iThink® software. It holds values for constants, defines external inputs to the model, calculates algebraic relationships, and serves as the repository for graphical functions.

Illustrative scenario. To explain how the SD model works is chosen a generic case of a part whose stock is 600. Deliveries to the assembler of refrigerators, factory demand (FD), are performed daily, according to his orders, the mean value of orders being of about 300 parts. Orders are delivered from stock, and the production department is notified about the production needs to replenish the inventory. The production of a batch of parts necessary to replenish the inventory is performed according to the following steps: installing the respective mould the injection machine, setting the operating parameters (pressure, temperature and cycle injection), initiating the injection cycles and recalibrating the parameters whenever the parts ambient temperature changes affecting the quality of the parts produced.

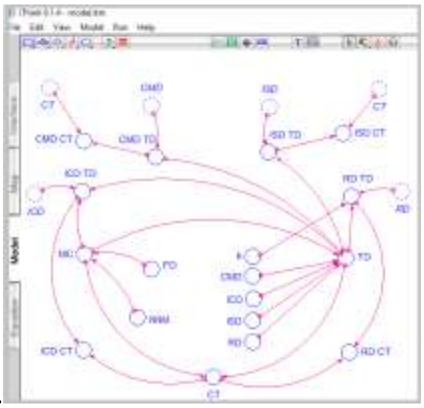

Fig. 4. System Dynamic model (print-screen from iThink software).

To analyze the production cycle-time, based on historical production reports, were considered the following approximately parameters: ICD = 0.7 min, CMD = 20 min, ISD = 10 min and RD = 2 min. The number of recalibrations was considered k = 4. Because these stages have stochastic durations in production cycle-time, they were defined into the model using the *NORMAL* function. The *NORMAL* function generates a series of normally distributed random numbers with a specified *mean* and *standard deviation* and samples a new random number in each iteration of a simulation. Therefore the syntax of ICD converter is [NORMAL(0.7, 0.1)], the syntax of CMD converter is [NORMAL(20, 2)], the syntax of ISD converter is [NORMAL(10, 1)] and the syntax of RD converter is [NORMAL(2, 0.5)]. The k converter is equal to 4. Another converter modelled represents the number of nests in mould (NNM), whose value is equal to 8. The functions of converters NIC, TD, CT, ICD_TD, CMD_TD, RD_TD, ICD_CT, CMD_CT, ISD_CT and RD_CT are defined by the equations (1), (2), (3), (4), (5), (6), (7) and, respectively, (8). Also, the model depicts the FD parameter defined with *NORMAL* syntax: [NORMAL(300, 15)]. After the parameters have been introduced in the model, 10,000 simulations were performed. The large number of simulations is motivated by the stochasticity of parameters, but also by the fact that the iThink® software computes equations very fast and easily. The values were exported in an Excel file and *average* and *avedev* functions were used to compute the *mean* and *standard deviation* of CT, ICD_CT, CMD_CT, ISD_CT and RD_CT. The results are shown in Table 1.

Table 1) Values of durations for production CT and sequences production cycle.

	CT	*CMD_CT*	*ICD_CT*	*ISD_CT*	*RD_CT*
Mean	1.708943	0.531973	0.682819	0.262539	0.258967
Standard deviation	0.00546	0.00341	0.002753	0.001361	0.002535

Conclusions

The objective of this research is to produce tools for the management of production systems. This paper reports the results of analysis on manufacturing cycle-time for a plastic part product. Analyzing the duration of an injection cycle cumulating value added activities with non-value added activities (Figure 5) is very useful both for dynamic simulation and for simulations with discrete event. The usefulness is due to the stochastic durations considering the stages totalling cycle-time.

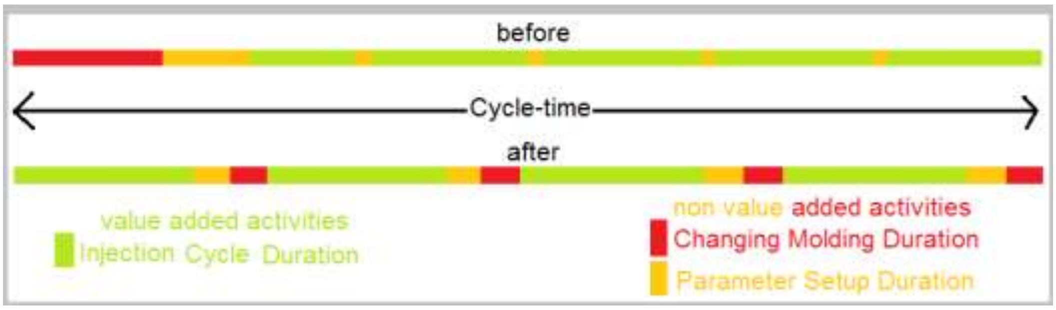

Fig. 5. Graphic visualization of cycle-time approach.

This approach aims to provide a framework for computing the production cycle-time. The SD model depicts the causal relations that exist between the parameters that influence the cycle-time. Modelling with the iThink® software allows stochastic simulations, which is favourable conditions of CT is defined, and easy integration in the next model describing the proposed manufacturing system.
Further research will analyze CT considering other factors such as the availability of moulding machine and defects rate in an attempt to reduce the safety stock. The purpose is to determine the optimal duration of cycle-time and to evaluate the consequence of the proposed technical-technological solutions.

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