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ANALYSIS AND IDENTIFICATION OF FLOATING CAPACITY BOTTLENECKS IN METALLURGICAL PRODUCTION

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The article constitutes a procedure for the analysis and identification of floating capacity bottlenecks in metallurgical production. The procedure conceived is based on the use of detailed capacity calculations, the output of which is the determination of the hourly output of the floating capacity bottleneck depending on the production schedule. Applying the said procedure is illustrated by the example of output analysis of a line for the cutting of hot rolled bars. Analysis and identification of the floating capacity bottlenecks subsequently becomes the starting point for applying the principles and tools of the Theory of Constraints (TOC) in material flow control in metallurgical plants.

Key words: *metallurgy production, floating capacity bottlenecks, output analysis, Theory of Constraints*

Analiza i prepoznavanje promjenljivih kapacitnih uskih mjesta u metalurškoj proizvodnji. Članak predstavlja postupke za analizu i identifikaciju promjenljivih kapacitnih uskih mjesta u metalurškoj proizvodnji. Postupak se temelji na rabljenju detaljno proračunatih kapaciteta, čiji izlaz je određen promjenljivim kapacitetima uskih mjesta u ovisnosti od proizvodnog asortimana. Primjena prikaznaog postupka je ilustrirana na primjeru rezanja valjanih čeličnih traka u toplom. Analiza i identifikacija promjenljivih kapacitnih uskih mjesta je i izvorište za primjenu "Teorije Constraints" (TOC) pri toku materijala u industrijskoj tvrtci.

Ključne riječi: *metalurška proizvodnja, promjenljiva kapcitno uska mjesta, izlazne analize, "Teorija Constraints" (TOC)*

INTRODUCTION

The contemporary development in material flow control in metallurgical plants leads to a vehement search for new control methods. The Theory of Constraints (TOC) elaborated by E. M. Goldratt [1] is increasingly more often considered a promising approach in this field.

Applying TOC in production control starts from an assumption that no production system will be so well balanced as not to contain a bottleneck. The bottleneck is the weakest element that determines the production system output. Any production element that disrupts the continuity of material flows in any way or limits the capacity utilization of other production elements may be regarded as a bottleneck [2]. That is why not only a device, but also a worker, missing material, energy, or lack of demand can be a bottleneck.

Considering that the economy of metallurgical production is closely connected with the optimal utilization of basic metallurgical aggregates that demand considerable investments and should not be limited by other production process components, capacity bottlenecks are regarded as the basic limitations in metallurgical plants. In general they can be defined as specific resources that disrupt the continuous flow of products through the production process [3] because of an apparent lack of available capacity.

The principles and tools of the Theory of Constraints have already found their practical application in various branches. This is evidenced, among other things, by the conclusions of a detailed study conducted by the American organization IMA Foundation for Applied Research based on a research in 21 American and European companies [4]. A characteristic of 7 companies that managed to implement the TOC tools with the greatest success is a part of the study. They all are production companies, most applications are in production control. None of the said companies belong to the metallurgical branch. What is the reason for this fact? The explanation can be found in one of the conclusions of the study performed: quick and easy TOC tool implementation depends on the character of the bottlenecks that occur in the given production.

The object of successful solution of most of the companies mentioned in the study was fixed bottlenecks. The fact that the positions of the said places in the production

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system do not vary, guarantees faultless control of all production operations and therefore the relatively easy application of the TOC tools.

But the key limitations in metallurgical production are the floating capacity bottlenecks, i.e. the workplaces or devices that tend to become bottlenecks depending on the portfolio of products processed. They are further characterized with additional characteristics making the situation still more complex:
- processing of a substantial extent of production portfolio,
- marked output differences depending on the production portfolio,
- lack of a simple functional dependence between portfolio composition and their output.

The line for the cutting of hot rolled bars may be an example of such a bottleneck:
- the production portfolio is a combination of bar diameters, trade lengths and ordered quantities, which represents tens of thousands portfolio items,
- depending on the production portfolio, the cutting line output may vary from a range of approximately 5 to 240 tons/hour,
- even in the case of cutting a very similar portfolio, a significant change in the line output can occur (for example increasing the trade length by 0.5 m can mean a change of line output reaching up to 100 % in some cases).

The mentioned character of bottlenecks significantly complicates applying the relatively simple principles and TOC rules for metallurgical production control. Putting them into practice is limited these days especially by the lack of knowledge and of systematic procedures for analysis and identification of floating bottlenecks in metallurgical production. So eliminating this shortcoming became the topic of the scientific research project by the authors.

APPROACHES TO THE ANALYSIS AND IDENTIFICATION OF FLOATING CAPACITY BOTTLENECKS IN METALLURGICAL PRODUCTION

According to [5] the following procedures for identification and analysis of capacity bottlenecks can be used in practice:
1. Observation and experience - wherever the bottlenecks are constant and products and processes are simple, the bottlenecks are usually known immediately. In more complex processes, will the presence of a bottleneck be indicated by the fact that stocks of unfinished production are repeatedly cumulated behind a certain workplace, or certain operations are always delayed.
2. Capacity calculations - these consist in determining the capacity requirements of the considered plan alternative and in comparing them with available capacity of individual workplaces. This capacity balance will allow determining the level of equilibrium and the capacity overload or underloading spots.
3. Computer simulation - simulation of the passage of the portfolio under consideration through the production system turns out to be a universal and efficient tool for finding out the capacity bottlenecks, especially the floating ones. The influence of various plan alternatives on production throughput, fulfilling the deadlines, or the costs can be simulated.

Based on the authors' experience from analysis and identification of specific capacity bottlenecks in metallurgical plants, the statement can be made that the first of the said options in itself can be utilized only to a limited extent. The bottleneck character nearly always requires the use of capacity calculations.

But the gross capacity calculations based on aggregated data (overall labour standards, general final product volumes etc.) only provide a reference view. They do not reflect the production sequence, batch size, or the need for reconstructions and adjustments. They are usually carried out for groups of workplaces and not for individual workplaces. So, especially in case of the floating capacity bottlenecks, they can be misleading.

Because the vast majority of capacity bottlenecks in metallurgical production are floating ones, it turned out to be a good practice to utilize detailed capacity calculations based on determining the available capacities of individual workplaces in the form of their hourly output depending on the production portfolio.

Performing a detailed analysis of organization and activity of individual workplaces is a necessary condition of completing the detailed capacity calculations. Such procedure is sufficient in cases where individual workplaces are:
- organized as a simple chain of serially arrayed workplaces,
- free from significant random influences (fluctuations of the processing time, device failures, and the like).

In the opposite case it is suitable, or eventually necessary, to supplement the detailed capacity calculations by applying a simulation. Composing a model of the production system and filling it in with data is an essential part of the simulation. In most cases it is possible to start from information obtained from an analysis of organization and activity of separate workplaces carried out in advance.

The report topic is a presentation of a procedure proposal for analysing the output of floating capacity bottlenecks in metallurgical production.

PROCEDURE PROPOSAL FOR OUTPUT ANALYSIS OF FLOATING CAPACITY BOTTLENECKS IN METALLURGICAL PRODUCTION

Carrying out the detailed capacity calculations requires obtaining and processing a relatively large amount of information and data. Unfortunately the information systems used in metallurgical production often fail to provide the necessary data, or their usability is difficult. That is why a series of partial analyses is necessary.

Based on the experience of the authors from the analysis and identification of specific floating capacity bottlenecks in metallurgical plants, the following procedure may be recommended for analysis of their output:

- an input analysis of individual production process factors,
- an analysis of production process organization on the floating bottlenecks,
- time studies of the floating bottlenecks,
- an analysis of the floating bottleneck activity in time,
- determining the hourly output of the floating bottlenecks.

The procedure proposed is based on a production organization scheme utilized in metallurgical plants. This is characterized by an exact differentiation of the production process into individual operations performed on specialized workplaces (production aggregates or devices). The workplaces are so distributed and arranged, that the working objects (materials and intermediate products) pass continuously through them in accordance with the time schedule for operations prescribed by the technological process. The production process is regularly repeated at constant time intervals (it is performed in production cycles), i.e. rhythmically.

An input analysis of individual production process factors

The basic aim of the input analysis of individual production process factors of the analysed production process is the determination of the potential floating capacity bottlenecks, which will become the object of further inquiry, as well as obtaining the initial information and data for the subsequent determination of their output depending on the portfolio processed.

Identifying and determining the intensity of all essential factors influencing the production capabilities of the investigated process is an initial condition for any capacity computations. Of all the factors, the areas of production facilities, production object, technology, and production organization [6] must be considered in the first place.

Production process organization analysis in floating bottlenecks

The aim of analysing the floating bottleneck process is to obtain an overview of the course of the production process from the entering of materials or intermediate products (working object) to the bottleneck, to their output in the form of a ready product, either intermediate or completed. Specifically, the determination of individual operations and production levels, of mutual relations between the operations and the levels, and of the passage of the working object through the workplace, are involved.

To visualize the mutual relations between the operations and the production levels, a flow chart can be used. To draw the path passed by the working object during the course of its processing on the workplace and to determine the transport distances, a circulation chart can be used [7].

Time studies of floating capacity bottlenecks

The aim of the time studies performed on floating bottlenecks is the determination of the average duration of individual production operations or their elements. If the operation durations depend on the processed portfolio, it is necessary to determine the appropriate functional dependencies.

In practice, operation snapshot (also called a time study) is used for these purposes [7]. To evaluate the results obtained, statistical data analysis is used, and in the case of operations whose duration depends on the processed portfolio, regression and correlation analysis are also used [8].

Analysis of the floating bottleneck activity in time

The aim of analysis of the floating bottleneck activity in time is to determine the rhythm (also called pace) of production on the analysed workplace. Because floating capacity bottlenecks are involved, the pace value will be expressed by means of a certain dependence on the portfolio processed.

The production pace is defined as the time interval between the beginning of two consecutive production cycles [9]. To determine its value, an analysis of the production cycle and of the organization form of the cyclic production process needs to be carried out.

Determining the hourly output of the floating bottlenecks

The last stage of the proposed procedure for analysing the output of floating capacity bottlenecks is the actual determination of their output. The aim is to deduce a formula for computing the hourly output of the workplace depending on the processed portfolio.

For the output P of cyclic processes for the duration of time T, the following general formula applies [9]:

$$P = \frac{T - t_p}{t} G \cdot k \tag{1}$$

where:

G - mass of the working object processed in one cycle,
k - production yield,
t - production process pace,
t_p - idle time of all the breaks occurring during the period T (time on repairs, device adjustments, and the like).

Considering that the aim of the analysis performed is to determine the hourly output of the floating bottleneck, it is possible to convert the formula to the following form (the time of breaks t_p is not considered while determining the output for a short time T):

$$P = \frac{60}{t} G \cdot k \tag{2}$$

where production pace is expressed in minutes.

OUTPUT ANALYSIS OF THE LINE FOR CUTTING OF HOT ROLLED BARS

The proposed procedure can be illustrated by the output analysis of the line for the cutting of hot rolled bars. The cutting line is a part of the metallurgical plant's Continuous Light Section Mill. The line output depends significantly on the processed portfolio. For a certain portfolio, the line causes a decrease in throughput of the rolling train, so representing a floating capacity bottleneck.

An input analysis of individual production process factors

a) *Means of production*:

The cutting line input links directly to the cooling bed of the rolling train. The basic cutting line equipment consists of two serially working grinding machines. Handling the bars is effected by platform lorries and then shifting them away from the cutting line with a lateral chain conveyor. The line is controlled from two control centres with one operator on each of them. The cutting line is followed by a dispatching section. Intermediate storage of the cut materials before or within the cutting line is not possible.

b) *Working object*:

The production portfolio processed by the cutting line consists of rolled bars:
- round, ∅ 16 - 70 mm,
- square, 20 × 20 - 60 × 60 mm,
- hexagonal, 13 - 66 mm.

The input material for the cutting is a layer of rolled products of a length less or equal to the working length of the cooling bed (107 m) and of a width less or equal to the width of the platform lorries (1,05 m). The rolled products are cut to bars of trade lengths of 3 - 12 m.

c) *Production technology*:

The cutting line performs a gradual processing of all the production orders designated for cutting. Each production order is specified with three parameters:
- bar diameter / mm,
- order quantity / t,
- trade length / m.

Depending on the said parameters, a certain number of rolled products on the cooling bed corresponding to the production order. The length of the rolled products exceeds several times the bar trade length, which corresponds to the cooling bed working length. The rolled production order is gradually cut into layers dictated by the platform lorry width. In effect, it usually includes several so-called complete layers that make the most of the cutting line platform lorries and one incomplete layer consisting of the remaining number of rolled products.

Depending on the resulting bar trade length, processing individual layers is done by means of one of two technological production methods - line activity modes:

Mode I. - for trade lengths in the range of $\langle 3, 8 \rangle$ m, the division of the rolled product layer is performed sequentially on both grinding machines. On the first machine, cutting the layer into the so-called batches, i.e. bars corresponding to a double trade length, is done. The second machine then cuts the batches into ready bars of the required trade lengths.

Mode II. - in the case of trade lengths in the range $\langle 8, 12 \rangle$ m, the layer is cut only on the first grinding machine to directly produce the required trade length.

d) *Production organization*:

From the point of view of trying to achieve a high utilization of the cutting line, cutting full layers of rolled products is optimal. Unfortunately, considering the customer requirements for smaller order quantities, the optimum is often unattained in practice.

Considering the complexity and extent of the cutting process, the continuing course of floating capacity bottleneck analysis is illustrated only by the main analysis outputs for the case of round bars of trade length 6 m.

Analysing the organization of the cutting line production process

Based on analysing the organization of the cutting line production process, two production levels and operations performed on these levels were identified:

Level I. - includes operations performed by the operator on the first grinding machine control centre

Level II. - includes operations performed by the operator of the second grinding machine control centre and of shifting the bars.

For trade length of 6 m, rolled products of a length of approximately 96 m divided into layers corresponding to the width of the platform lorries are the input for the cutting line. The following technological procedure is conducted during the layer processing (cutting line activity mode I.):

- facing section of the layer front on the first grinding machine,
- gradually cutting the layer on the first grinding machine to 8 batches,
- gradually cutting the batches on the second grinding machine to the final trade length,
- shifting the ready bars to the dispatching section.

The technological procedure of processing the production order for ready bars of trade length of 6 m is depicted in Figure 1.

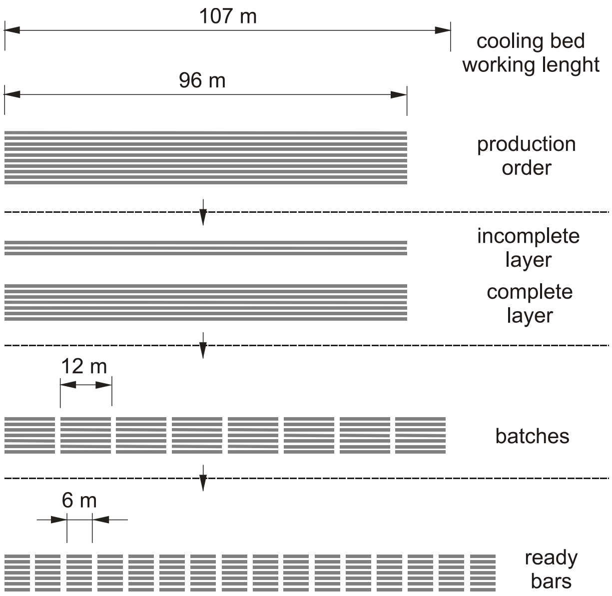

Figure 1. **Technological procedure of processing the production order for ready bars of trade length of 6 m**

Slika 1. **Tehnološki postupak izradbe narudžbe za gotove šipke dužine 6 m**

The cutting line output is then dictated by the slower production level II., where the operator also shifts the bars away in addition to cutting them. Six operations decisive for the cutting line output were identified on the said level. The said operations link continuously to one another and they are always repeated eight times during dividing one layer of rolled products to the trade length of 6 m.

Time study of the cutting line

Time measurement has been performed in order to determine the time characteristics of the identified operations. Processing the measured data took place in the STATGRAPHIC software tool. The observed operations were divided into two groups:

1. Operations, the duration of which does not depend on the portfolio processed - this group includes manipulation operations with the batch and with the ready bars, fixing the batch, and shifting away the ready bars. Statistical analysis of the measurement results has been carried out to determine their average duration. Their total duration is $\overline{t_1}$ = 1,083 min.
2. Operations, the duration of which depends on the portfolio processed - only the operation of cutting on the second grinding machine falls within this group. Regression analysis and correlation analysis have been used to determine the formula for computing the average cutting time ($\overline{t_2}$) depending on the portfolio processed. The tightest dependence was shown by the linear regression model in the form:

$$\overline{t_2} = 0{,}133 + 0{,}0000167 \cdot S_ř \tag{3}$$

where the section area in mm^2 ($S_ř$) is the independent variable and $\overline{t_2}$ is in minutes.

Analysis of cutting line activity in time

From the analysis of the course of processing production orders on the cutting line, a formula for computing the production order processing pace (t_z) has been deduced in the following form:

$$t_z = t_{vp} \cdot p_{vp} + t_{vn} \tag{4}$$

where:

t_{vp} - processing pace of one full production order layer / min,

p_{vp} - number of full layers in an order,

t_{vn} - processing pace of one incomplete production order layer / min.

The above formula respects the fact that the production order usually consists of several complete layers and one incomplete layer.

Considering that the operations decisive for the cutting line output are always repeated eight times on each layer, the formula for computing the processing pace (t_v) of a certain portfolio layer assumes the following form:

$$t_v = 8 \cdot \left(\overline{t_1} + \overline{t_2}\right) \tag{5}$$

So after substituting for $\overline{t_1}$ and $\overline{t_2}$, and after modifications, the following applies:

$$t_v = 9{,}728 + 0{,}0001336 \cdot S_ř \tag{6}$$

The formulas for computing the number of full layers in an order (p_{vp}) and the section areas of a given order's complete and incomplete layers ($S_{řp}$, $S_{řn}$) were deduced based on the information from the bar rolling and cutting technology used in the given process and due to their complexity, they will not be further analysed.

Determining the hourly output of the cutting line

Based on the formula (2), the following formula can be used for computing the cutting line output during processing the round bar of trade length of 6 m:

$$P_{DL} = \frac{60}{t_z} \cdot m \tag{7}$$

where:

P_{DL} - cutting line output (tons/hour),
t_z - production order processing pace (min),
m - order quantity (tons).

CONCLUSION

The analysis of output of floating capacity bottlenecks in metallurgical production allows the determination of:
- the production portfolio that causes a bottleneck to appear on the analysed workplaces,
- capacity possibilities of floating capacity bottlenecks in the case of the most common portfolio,
- production portfolio ensuring a maximum output of the floating capacity bottleneck.

The mentioned procedures can be used in practice, especially in the following directions:
- for operative planning and production control with an aim to optimising the throughput of the production process for the specific portfolio structure designated to be processed in a given period,
- for composing rules designed for adopting such a production portfolio structure that would facilitate the efficient utilization of the basic metallurgical aggregates from the point of view of the available capacity of the floating bottlenecks,
- for application of TOC tools designed for the production branch, especially the Five Focusing Steps for Ongoing Improvement and the DBR (Drum-Buffer-Rope) system.

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