Theory of Constraints in Machine Dynamics and Steelmaking Processes

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Abstract. The article describes the potentiality of applying the theory of constraints and the structural risk analysis ideas for production machines and operating procedures applied in basic metallurgical production that are subsequently developed by the authors, which is rather new and of great current interest from the scientific perspective. "Blast furnace – oxygen converter" remains the most common type of process flow used in high-grade steel manufacturing today. The existing reality tree, the problem solution diagram and the future reality tree are presented and analyzed. The transition objectives and the plan for modifying structures of the metallurgical cranes used at the oxygen-converter shop of the steelmaking plant are identified. It is shown that the metallurgical overhead cranes can represent the "bottleneck" and their failure or accident can cause serious losses, and not only economic ones. The improvement of the converter productivity is proposed as the desired outcome, which, in turn, will have a significant impact on the efficiency of the entire complex engineering system under discussion. Increase in the number of annual operating days is regarded as the objective of the transition and the evaluation of the metallurgical crane quality based on the structural risk analysis is considered to be the objective of the modification. Information provided in the article can be used to optimize basic operating procedures applied by steel plants and develop their digital twins and software.

Keywords: Quality evaluation · Metallurgical production · Metallurgical crane · Converter · Theory of constraints · "Bottleneck" · Reality tree

1 Introduction

Structural risk analysis represents an essential part of steelmaking quality evaluation [1–14]. Considering the fact that accidents and suspension of this production can cause serious economic and other losses, it is necessary to change the procedures for managing such production and the machines used in it. The application of the theory of constraints here, which was developed in the 1980s by Eliyahu Goldratt [15–18] and elaborated in the following papers [19–23], appears to be interesting, new and of great current interest. The theory of constraints implies the identification of the most significant constraining factor (i.e. the limitation) that must be overcome to achieve the target, which

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is followed by the systematic minimization of this limitation for as long as it does not represent a constraining factor any more. In production, this limitation is referred to as the “bottleneck”. The application of the theory of constraints allows to increase profit and production output.

It is assumed that most systems have only one constraint but sometimes a system can have two or three constraints.

Let us consider that the existing group of metallurgical overhead cranes represents the “bottleneck” in oxygen-converter production. These cranes constitute hazardous production facilities and their interruption or accident significantly reduces the efficiency of steel production.

2 Research Goal

The existing condition of the steelmaking industry can be described by the use of one of the basic types of process flows, i.e. “blast furnace – oxygen converter”. It allows to obtain high-quality steel products and has satisfactory productivity, simple equipment design and high operating flexibility [24].

The goal of this article is to apply the theory of constraints to the machines and the production process used at the oxygen-converter shop of the steelmaking plant in order to improve the efficiency of this system.

The efficiency of the system under discussion is associated with the production capacity of liquid steel, which is determined by the availability of operating converters (according to the system used in Russia, there are either two converters in total including one in operation or three converters in total including two in operation), their capacity and productivity, heat duration and the number of annual operating days. Considering that the group of metallurgical overhead cranes used at the oxygen-converter shop represents the “bottleneck” of the production process, we shall construct the existing reality tree, the problem solution tree, the future reality tree and the modification plan, which is based on the transition plan.

The quality of the crane structures is suggested to be evaluated at each stage.

3 Research Materials and Method

The converter shop consists of scrap metal, converter and charging bays, a bay for slag ladle rearrangement and a ladle section. Different metallurgical cranes are used in every bay including cranes for chute rearrangement, magnetic cranes, casting (charging) cranes, overhead cranes and so on. We shall construct the existing reality tree for the structures of the cranes used at the oxygen-converter shop of the steelmaking plant based on the fact that the crane structures as well as their interruptions, accidents and breakdowns have a significant impact on the entire production cycle at the oxygen-converter shop as presented in Table 1.

It is a well-known fact that more than 80% of metallurgical cranes are operated after the expiry of the specified service life [1–3]. For this reason, the existing reality tree will address the two key problems: structures of the cranes that are used either after the expiry of the specified service life or before the beginning of it. Accidents or disasters that occur with these structures are assumed to be rare [1–4] and their prevention associated with failures and unscheduled maintenance results in lower productivity of the converters and the oxygen-converter shop in general, which is certainly unacceptable. Therefore, they are identified as undesirable events.

Table 1. Existing reality tree for structures of the cranes used at the oxygen-converter shop.

Actual reasons, key problem	Intermediate outcome	Undesirable events
Structures of the cranes used after the expiry of the specified service life	Analyzing the quantity and the material of the structures, evaluating the actual technical condition and the probability of failure	Failure, accident, disaster, idle time, unscheduled maintenance, reduced converter productivity
Structures of the cranes used before the beginning of the specified service life	Analyzing the quantity and the material of the structures, evaluating the technical condition and the probability of failure	Failure, accident, disaster, idle time, unscheduled maintenance, reduced converter productivity

The key problem is defined at this stage. In other words, it is decided whether the structure needs to be repaired or withdrawn from operation. In particular, metallurgical cranes that are used after the expiry and before the beginning of the specified service life represent the key problem here. After performing the analysis and identifying the intermediate outcome, we shall move on to the next stage.

This is followed by constructing the tree for solving the operational problems existing at the oxygen-converter shop as presented in Table 2.

Table 2. Tree for solving the problems existing at the oxygen-converter shop.

Objective	Prerequisites	Supporting methods
Minimizing the probability of accident, failure, idle time and unscheduled crane maintenance	Monitoring the stress-strain behavior of the crane structures, calculating the probability of one of the following crane structure conditions: normal, limiting permissible and critical	Operational log records, digital twin of crane operation, software

The objective of minimizing the probability of accidents, failures, idle time and unscheduled crane maintenance must be achieved in order to solve the problems.

The stress and strain fields of the load-carrying structure of the metallurgical overhead crane are calculated for the purposes of monitoring the stress-strain behavior of the structures. The calculations can be made when the first limiting condition is met, i.e.

when the stress level within certain areas reaches the yield strength of the girder. Various software tools can be used here. In addition, members of the responsible group must be determined and different sources of crane-related information must be identified and described here. Different limitations on benchmark data and financial resources must also be defined at this stage.

The description of the properties of the probabilistic load density functions for actual stresses and strains determined by the loading time and conditions $f(\sigma_{ij}, t), f\left(\varepsilon_{ij}, t\right)$ on the assumption of a particular pattern of random processes is required as auxiliary elements for the quality evaluation. Given that heavy loaded machines are operated under established conditions, it can be assumed with a certain degree of accuracy that such random processes represent stationary Gaussian processes with calculated expected values and variances.

The load-carrying structure includes the following:

- steel structures of the bridge including longitudinal and edge girders of main and auxiliary bridges, welding areas between the brackets of connecting bridge passages and the girder webs, lower girder booms;
- longitudinal girders of the auxiliary bridge;
- crossbeam of the main hoisting mechanism including the hooks, steel structures of the crossbeam;
- ratchet gear of the main hoisting mechanism including the ratchet wheel, pawls, pawl mounting axes, hold-down springs, ratchet wheel mounting axis.

The conditions provided in Table 2 have already been suggested in [3] and are limited as follows: normal (the probability of accident risk is 0.159), limiting permissible (the probability of accident risk is 0.521) and critical (the probability of accident risk is 0.749)

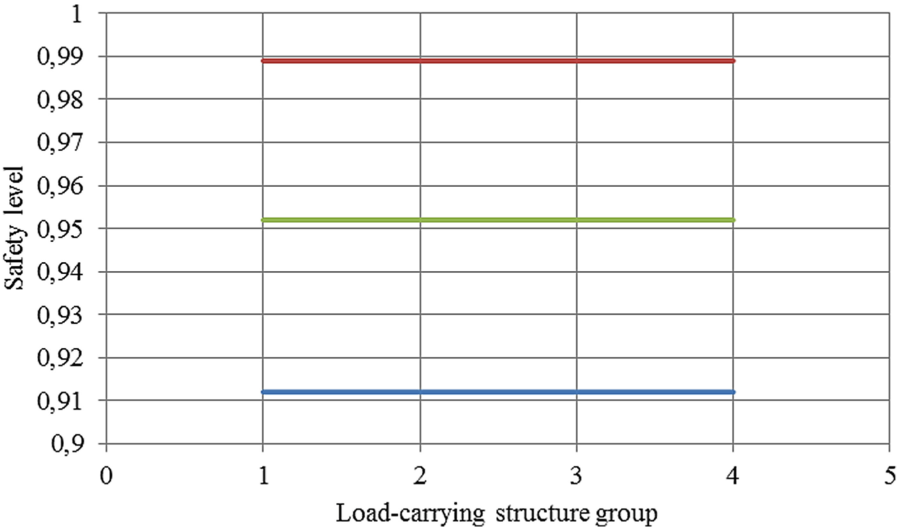

Fig. 1. Safety levels for the four groups of the load-carrying crane structure.

conditions. As a result, safety levels were obtained for each of the four groups of crane structures (Fig. 1) [3].

The safety levels are decreased as a result of operation, which shortens the safe life of the metallurgical crane. The crane can be operated when repair and recovery activities are performed at the expiry of its safe life and after carrying out provisional and general inspection based on the above safety levels (Fig. 1). Otherwise, any further operation can result in accidents, disasters, and, subsequently, losses that can be incomparably higher than the cost of the repair and recovery activities.

Hence, we can illustrate the future reality tree for the oxygen-converter shop of the steelmaking plant as shown in Table 3.

Breaking through and achieving the target (Table 3) assume that the converter productivity is increased or constant but not decreased.

The converter productivity $П_к$in tons per annum will be calculated using the following formula [24]:

$$П_к = \frac{1440 \cdot \alpha \cdot Ф \cdot T}{100 \cdot \tau} \tag{1}$$

where 1440 is the number of minutes in a day, α is the percentage ingot yield relative to the liquid steel weight, which is taken as 90–97%, Φ is the number of annual operating days, T is the converter capacity (based on the liquid steel weight) in tons and τ is the heat duration in minutes.

Table 3. Future reality tree for the oxygen-converter shop.

Breakthrough	Intermediate outcome	Desired outcome
Operational log records, digital twin of crane operation, software	Withdrawing the cranes that are in pre-accident condition from operation, optimizing the time between maintenance, spot repair of the structures	Minimizing the number of failures, accidents, disasters and idle time, optimizing the equipment and the structures, improving the converter productivity

It is clear that the number of annual operating days (Φ) will depend on the converter operation management at the oxygen-converter shop, the number of converters and the accident-free (no-failure) operation of the cranes. Assuming that a crane can be unexpectedly interrupted or damaged, we can only imagine the eventual consequences that might occur as a result. Therefore, the objective of increasing the number of annual operating days (Φ) by minimizing failures and accidents of the structures of the cranes used at the oxygen-converter shop can be added to the transition tree of the theory of constraints for the system under discussion. Achieving this objective can be prevented by the lack of personnel qualification and inaccurate evaluation of the actual technical condition of the crane structures. For this purpose, it is necessary to implement the plan for modifying the quality evaluation applied to the structures of the cranes used at the oxygen-converter shop of the steelmaking plant as presented in Table 4.

Table 4. Plan for modifying the quality evaluation applied to the structures of the cranes used at the oxygen-converter shop.

Action	Intermediate outcome	Objective
Quality evaluation of the crane structures based on the structural risk analysis	Withdrawing the cranes that are in pre-accident condition from operation, optimizing the time between maintenance, spot repair of the structures	Minimizing the number of failures, accidents, disasters and idle time, optimizing the equipment and the structures, improving the converter productivity

Therefore, the structures of different types of cranes will be considered as the “bottleneck” of the oxygen-converter shop at this stage.

4 Research Findings and Discussion

We shall illustrate an example of how the theory of constraints can increase the productivity of the converter and, subsequently, the entire oxygen-converter shop.

The oxygen-converter shop has three converters, one magnetic overhead crane, one overhead crane with tongs, two overhead cranes for cast iron ladles, two overhead cranes for scrap chutes, two overhead cranes for empty steel ladles (with 200 ton lifting capacity), four overhead cranes for steel ladles (with 500 ton lifting capacity) on the continuous slab casting machine line and four overhead cranes for industrial and slag ladles located in the same area. There are 16 overhead cranes at the shop. We shall evaluate the quality of the structures of the metallurgical cranes based on the probability of their safe (accident-free) operation [1–3] as presented in Table 5.

The following designation is used here: S1 is the normal, S2 is the limiting permissible and S3 is the critical lifting capacity of the crane. The numerical values show the probability of one of the conditions and the probability of transition to another condition. The findings were obtained by simulating Markovian processes, which allowed to find the limit probabilities in steady-state conditions.

By having the actual data on the crane load and monitoring their condition we can improve the efficiency of the system under discussion while taking into account the following constraining resources: the capacities of the shops must not be reduced and the quality of the cranes is low.

Table 5. Lifting crane capacity during the operation.

Years in operation	S1	S2	S3
0	0.84	0.48	0.25
15	0.43	0.35	0.24
25	0.32	0.29	0.39

Considering that the oxygen-converter shop capacity ranges between 2.6 and 11.6 mln tons per annum [24] depending on the converter capacity, an increase in no-failure (accident-free) operation by one day will improve the shop capacity from 0.12% to 0.28%, which is very significant.

This approach can be used to plot a graph illustrating the effect of the number of annual operating days on the productivity $П_к$ of the converter with varying capacity as shown in Fig. 2.

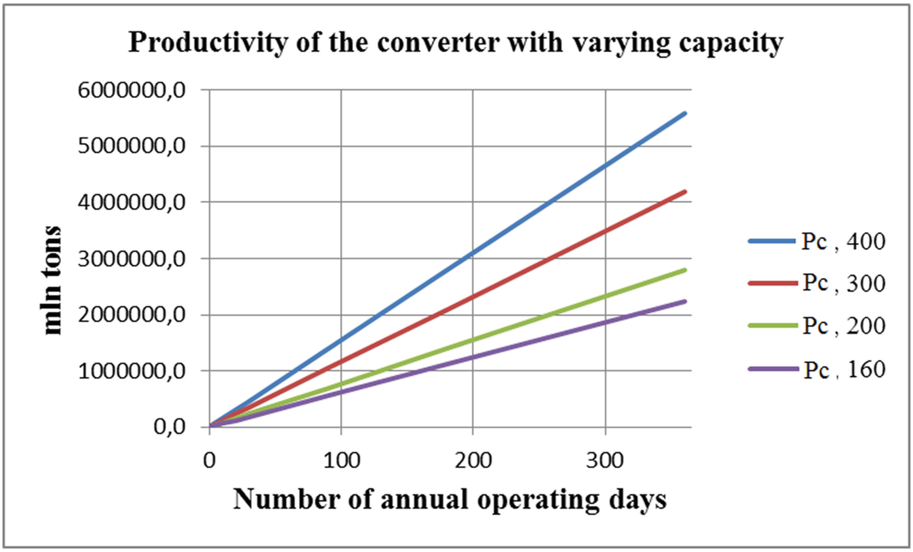

Fig. 2. Productivity of the converter with 400, 300, 200 and 160 ton capacity depending on the number of annual operating days.

After evaluating the quality of the structures of the metallurgical cranes used at the plant and preparing their optimization program with reference to the theory of constraints and on the basis of such evaluation, we can increase the liquid steel capacity of the shop. The program must be structured in such a way that the number of operating days with accident-free (no-failure) performance is increased. Regular preventive measures must be taken at the same time without necessarily waiting until accidents or failures occur.

Recommended scope of the proposed optimization program:

- evidence that the inspected crane, its load-carrying structure and elements comply with the documents regulating its safe and no-failure operation;
- reading operational and technical documentation;
- putting the main structures of the crane in place;
- compliance of the electrical power supply with the documents regulating its safe and no-failure operation;
- calculating the probabilistic loading of the crane, constructing the working stress and strain density functions and analyzing the actual technical condition of its load-carrying structure;

- evaluating the quality of auxiliary structures.

By analyzing the group of 16 metallurgical cranes we shall determine their quality based on the structural risk analysis, the quantity of evaluated cranes and the number of annual operating days for every crane structure.

Therefore, the following algorithm can be suggested to evaluate the quality of the cranes used at the oxygen-converter shop of the steelmaking plant during the operation and after the expiry of the warranty period:

- analyzing all the information and the documentation related to the crane structure;
- on-line diagnostics and expert survey;
- analyzing the mechanisms of damage degradation and escalation;
- assessing the quality in scores or conventional units based on the normal, acceptable and critical (disastrous) risk criteria;
- making a decision regarding the crane: overall reconditioning, reducing the working parameters and further operation, dismantling or disposal.

The “bottleneck” and the number of annual operating days can be determined based on the above. The productivity of the converters and, therefore, the entire shop can be determined according to Fig. 2.

The suggested application of the theory of constraints can also be used to develop standards and special technical regulations for evaluating quality and risk associated with hazardous production facilities and to perform probabilistic safety analysis. “Bottlenecks” can also be referred to in process management.

5 Conclusions

The theory of constraints has high potentialities to manage complex technical systems, machines and manufacturing processes. These systems and processes include basic metallurgical production shops such as the oxygen-converter shop for liquid steel production. Structural risk analysis allows to evaluate the quality of the operated equipment structure in terms of the load-carrying structure. Such synthesis is relatively new and of great current interest today. It allows to identify the process “bottlenecks” and address production management and optimization in a timely manner.

Given the existing constraints, the real oxygen-converter process and the 16 metallurgical overhead cranes, we provided an example of the efficiency of this approach and made a conclusion that the oxygen-converter shop capacity ranged between 2.6 and 11.6 mln tons per annum [24] depending on the converter capacity. In addition, an increase (decrease) in no-failure (accident-free) operation by one day will result in a rise (drop) in the shop capacity from 0.12% to 0.28%, which is significant under the present-day conditions.

The construction of the existing and future reality, problem-solving, transition and modification plan trees for a specific machine or process allows to draw a conclusion regarding the potential of this research.

The information provided in this paper can be applied in economic analysis, production planning and metallurgical machine dynamics study and optimization.

The specific complex “blast furnace – oxygen converter” technical system was used as an example to test the new application of the theory of constraints in machine dynamics and operating procedures related to metallurgical production, highlight the key problems, identify the “bottleneck” of such manufacturing process and determine the main factor influencing its efficiency. This factor is the number of annual operating days that can be calculated and applied in combination with the original procedure for evaluating the quality of metallurgical cranes based on the structural risk analysis. Compared with other popular methods, the suggested application is adapted to metallurgical production and described as simple and time-efficient when making scientifically grounded technical decisions.

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