Experience of putting into practice and development prospects of digital twins in section rolling technological systems

***S. A. Levandovskiy**, Cand. Eng., Associate Prof., Dept. of Metal Processing Technologies [1],*
e-mail: levandovskiy@mail.ru;
***A. B. Moller**, Dr. Eng., Prof., Head of Dept. of Metal Processing Technologies [1],*
e-mail: amoller@mail.ru;
***O. N. Tulupov**, Dr. Eng., Prof., Vice-Rector for Research and Innovations [1];*
***N. A. Baranov**, Post-Graduate, Dept. of Metal Processing Technologies [1]*

[1] Nosov Magnitogorsk State Technical University (Magnitogorsk, Russia)

The authors consider the problem of creation, development and putting into practice digital twins for technological processes. Use of digital technologies in metallurgy allows to cut the expenses of manufacturing process, to improve quality of metal products and to widen their grade and dimension ranges. The leadership of Magnitogorsk Iron and Steel Works (MMK) formulates the ambitious aim to create a digital twin for a full-scale technological site, with consequent distribution of a digital platform to the whole enterprise. As soon as production stage is the main part of each metallurgical company, providing receiving of the required profit, stage-by-stage achievement of the formulated goal is starting from the industrial component. Step-by-step process of creation of a digital twin is considered for the section rolling mill 170 at Magnitogorsk Iron and Steel Works. This technological process is also combined and can be presented as separate conditional blocks, such as metal heating, rolling and cooling. Based on the positive result of the successfully realized project of the digital twin for the air cooling lines, it was decided to use this practice to the whole technology of manufacture of section products at MMK 170 rolling mill. The main aims and tasks for the examined project are formulated, it will allow to obtain the first Russian experience of creation of the full-scale digital twin of an industrial object. The features of operation of up-to-date digital twins are considered and the functional restrictions are defined. Structural scheme of the created complex dynamic mathematical model was designed as the base for operation of the ready solution. Expected industrial effects were formed in narrow cooperation with MMK specialists. Taking into account the technical and technological risks, the restrictions for implementation of the digital twin are determined: operation in the advising conditions, use of the complete data spectrum about the object for full-range possibility of digital copy simulation, industrial testing in the real operating conditions of the rolling mill until achievement of preset authenticity. When considering the prospects of creation of similar solutions for other technological objects (rolling mills or other technological stages), up-to-date features of their further development and integration within the company range are revealed. They testify that created digital twin can be a universal testing field, promoting appearance of domestic integration platform for digital twins. Import substitution in this industry is critically important for Russia, because there no such technical solutions at the national market.
Key words: section rolling production, section mill, digital twin of the technological process, modeling of the technological process, section rolling technological system, industry 4.0, digitalization.
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Introduction

At present time, digitalization of metallurgical production facilities is strictly required process, as any other process, which is controlled and accompanied by the company within the framework of realization of its own basic activity. Use of different information technologies became rather conventional and ordinary event in the conditions of active development of industrial enterprises, starting from intensive putting into practice of automation systems (Industry 3.0) [1, 2].

Otherwise industrialization of the end of XIX century – beginning of XX century, the modern digital revolution (Industry 4.0) is very quickly developing and covers various kinds of activity [3]. The future world can be seen only through the prism of digital collaboration; it relates also to complex metallurgical works. Today it is difficult to imagine an industry, where many technologies from different engineering directions of human activity – from mine surveying matter to BIG DATA processing systems and neural network analysis are combined in such amount. This fact testifies that the task of digital twin (DT) creation of the whole metallurgical enterprise is a complicated problem [4].

Many Russian metallurgical works chose the way aimed on development of digital technologies, where digital copy of the whole enterprise with all its processes and objects can be considered as one of the results of global digitaliza-

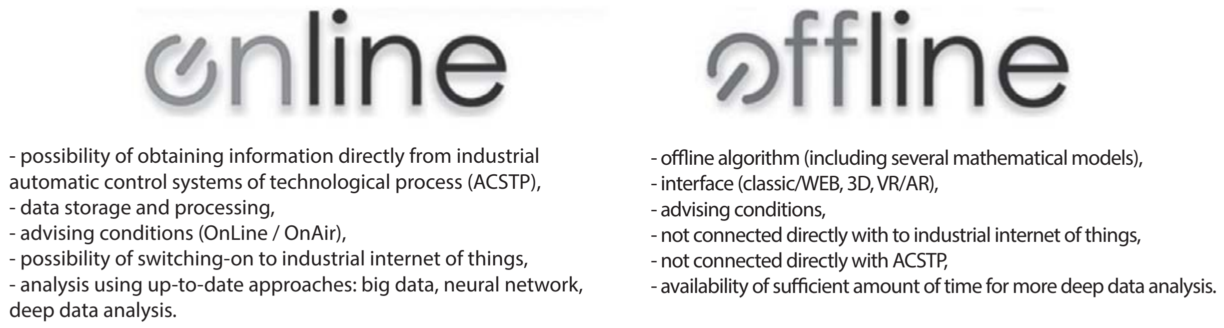

Fig. 1. Online and Offline features of digital twins

tion. In this case even the personnel to some extent will be examined as an information object with its own kinds of input and output data. Magnitogorsk Iron and Steel Works (MMK) also was not an exception from this point of view; step-by-step creation of the digital twin of the works is one of the aims formulated by the leadership of this enterprise. Other large Russian metallurgical companies stand similar ambitious tasks for their development [5].

Metallurgical enterprise consists of the complex of departments, which can be conditionally divided by two functional blocks: of production and non-production purpose. Each of these blocks has its own special management features, which should be taken into account during forming the DT concept of an enterprise. From the formal point of view, a metallurgical company (plant or integrated works) never can become a full digital enterprise, because production is its main direction of activity for getting profit, while digital transformation can only maximally possibly rise the efficiency of technological and accompanying non-production processes.

Taking into account the modern technologies in designing, development, creation and putting into practice of digital twins, a large metallurgical enterprise can be presented as a system, which will be filled step-by-step by different objects with various complication level [6, 7]. Such approach is close to distribution of automatic control systems within company's departments and is its logical continuation.

Experience of use of the system theory can show in this case, that putting into operation of such technically complicated and scientific-intensive objects as digital twins can demand significant consumption of resources (financial, intellectual, human and temporary). Each information system is devoted first of all to cutting of expenses. DT also is considered as a modern type of such system and allows to reduce different kinds of expenses in various processes; however, totality of digital twins makes it possible to get synergetic effect and to provide essential effect on operation efficiency both of separate technological processes and the whole industrial enterprise.

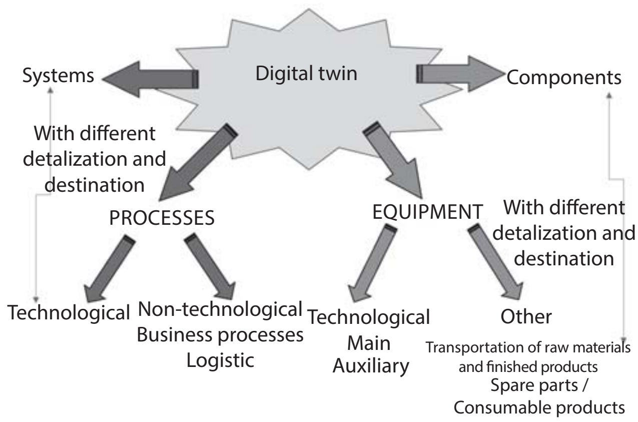

Fig. 2. Objective classification of digital twins

Aims and tasks of the research

Creation of DT in the modern digital world is the next natural step for development of mathematical models, which increases efficiency of their use. From the terminological point of view, there are several DT identifications, but they all mean that this is a virtual interactive copy of a real physical object or process, which allows to provide management of this object or process via optimization of the business operations. This paper describes the complex of technological processes, which implement the technology, as a partial case of the business process.

Depending on the variants of interaction with other systems, DT can be **online** and **offline** (**Fig. 1**). DT also can be reflection of the components and systems (**Fig. 2**). Digital twins "Prototype", "Instance" ("Ekzemplar") and "Aggregated DT" can be used (**Fig. 3**) [8].

Let us examine DT of technological processes (see Fig. 2). It is possible to emphasize separately several technological metallurgical processes, which can be conditionally considered as independent and finalized ones. As a rule, the fact that such process can be realized independently from other technological processes is a sign of such process; the metal rolling process in a section mill can be the example. After DT creation, it is possible to collect the

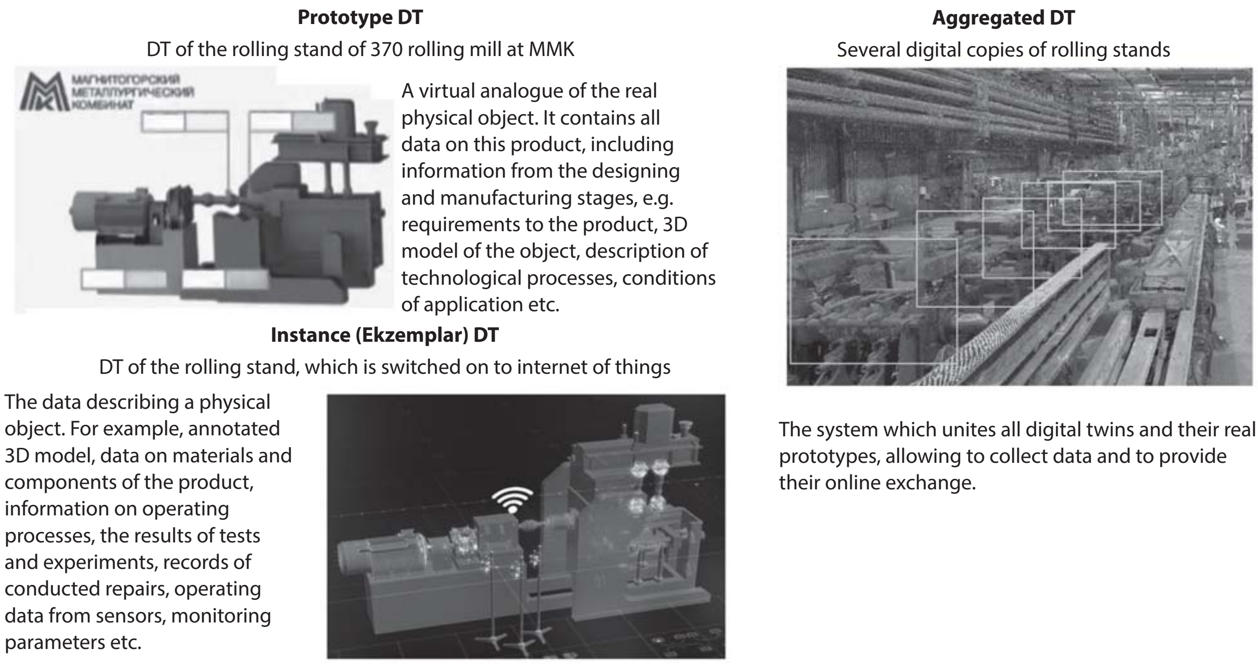

Fig. 3. Functional and scale classification of digital twins

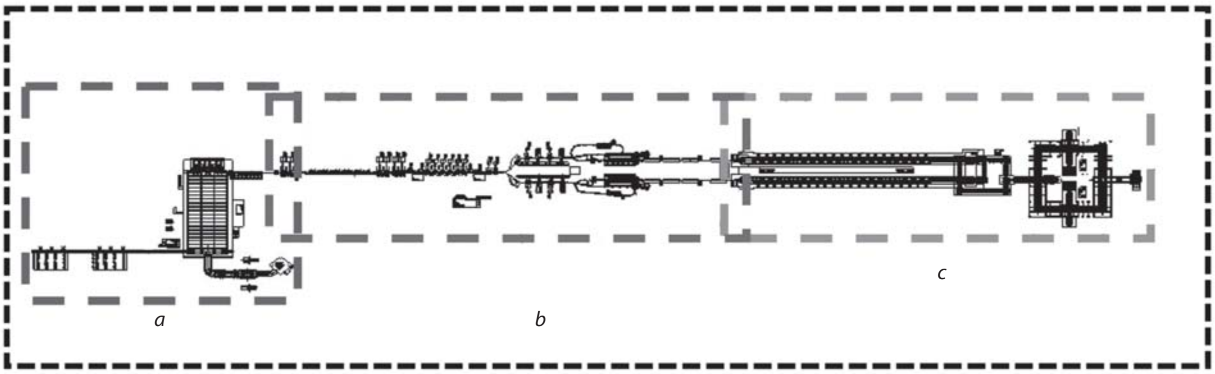

Fig. 4. The blocks of technological processes for their simulation in the DT of 170 rolling mill (*a* — billet heating; *b* — metal forming process; *c* — metal cooling).

technological chains as a construction set, i.e. with transitions to metallurgical stages.

The same principle is considered also for creation of DT for technological process of metal rolling at section mill. The process can be divided by separate stages and realized via their modeling, with potential prospective of their incorporation (**Fig. 4**).

As soon as creation of DT of technological process is a complicated task, dividing of the technology by separate stages can help to realize the general task of DT forming for the whole technological chain step-by-step. This paper presents consideration of this process in details.

Let us underline several features that were taken into account during creation of DT for the part of technological process (air cooling line for the section rolling mill 170 of MMK):

- DT for the part of technological process is created as a model [9], which has formalized system (description of mathematical models and experimental results is presented in the work [10]) as well as input and output signals (data flows) with the following sources: level 0 of ACSTP (operative information about the process state); information from the previous technological stage about billet, state of equipment and internal systems (for example, accounting system for rolling rolls); additional network of measuring remedies (industrial internet of things IIoT) [11. 12];

- at the stage of building DT of separate components of the technological process (section rolling), e.g. air cooling line (Fig. 4, c), the solution was taken that such DT will operate in the advising conditions [13], because feedback forming and interaction with the levels 1 and 2 of ACSTP is possible in well adjusted system, where DT will

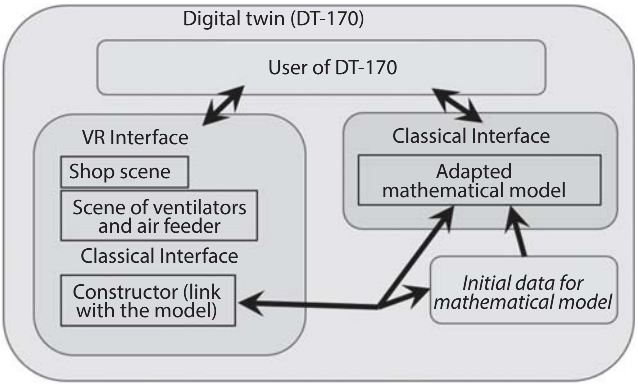

Fig. 5. Structure of interaction in DT of the air cooling line at the rolling mill 170

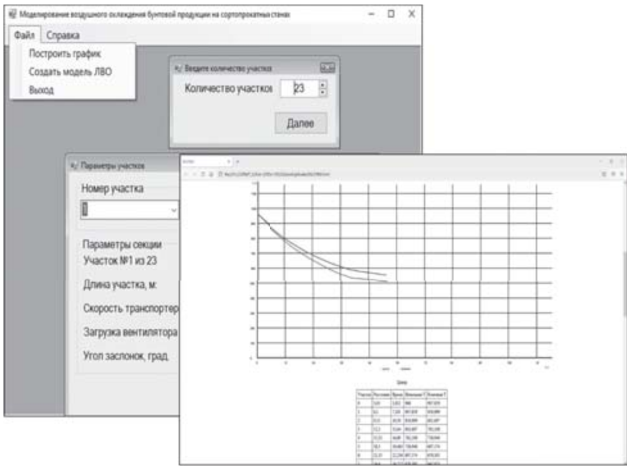

Fig. 6. Classical interface of DT for the air cooling line of 170 rolling mill

be incorporated in more complicated DT of the whole technological process at rolling mill;

- DT operation both for the part and the whole technological process should be proved experimentally to provide previously preset modeling authenticity, which should be not less than 0.85 (assessment was carried out via statistical methods, with comparison of simulated and measured parameters).

Now let us determine the aims and tasks of the research.

The aim of the research is forming of transparent methodology of digital twin creation for a technological process (the pilot process is the technological process with manufacturing products at the rolling mill 170 of MMK) via stage-by-stage designing and putting into practice.

The following operations can be related to **the tasks of the research**:

- creation of the pilot DT of the part of technological process with manufacturing products at the rolling mill 170 of MMK (implemented for the air cooling line) [10];
- development of the detailed concept of DT building for the whole technological process at the rolling mill 170 of MMK;
- adaptation of mathematical models: metal heating (Fig. 4*a*), metal rolling (Fig. 4*b*), metal water and air cooling (Fig. 4*c*), metal transportation and interaction with the auxiliary equipment (shears, pinch roll units etc.) for their mutual integration and integration with the sources of primary information from the rolling mill;
- forming, mastering and testing of the common dynamic mathematical model of DT for the rolling mill 170;
- development and integration with the finished DT of interaction interfaces (classical in advising conditions and VR in the conditions of demonstration and simulation);
- industrial testing and putting into operation.

Practical realization

Within the framework of the scientific-research and pilot-engineering work “Evaluation of the prospects and determination of the strategy for putting into practice the technology dor production of sorbitized wire rod in operating conditions of the rolling mill 170, according to the requirements of MMK-Metiz JCS and on the base of creation of the digital twin of modernized accelerated cooling lines”, DT for the air cooling line as the part of the whole technological chain was developed. The mathematical model, which was used as the base for this digital twin, was adapted to the technological conditions and is characterized by wide area of application [14-17]. This DT was successfully tested, the results of its operation were put into practice as modified cooling procedures and introduced in the technological specification of the rolling mill, while DT itself was put into operation [9, 10, 13]. Interaction structure in this DT (it operates Offline in advising conditions) and screenshots of its interfaces are presented on the **Fig. 5-7** respectively.

Classical interface (see the Fig. 6), web interface interaction, interfaces of virtual and added reality are mostly distributed interfaces of interaction with DT program code in the modern practice [18, 19].

The following expanded results of DT use for the air cooling line of 170 rolling mill can be noted:

- development of three-phase strategy for mastering of the technology for manufacture of sorbitized wire rod;
- formulation of recommendations for improvement of the air cooling line (on the base of the developed strategy);
- development of the technical assignment for conduction of engineering works aimed on preparation of the detailed information about further steps of improvement of the air cooling line, in order to obtain the preset combination of mechanical properties of manufactured products and to expand dimension range of the rolling mill.

To provide integration of the created DT for the air cooling line with potentially created other DT components of the whole technological chain, the following actions are necessary:

- development of the detailed concept of the whole DT structure for the rolling mill 170;
- examination of the key functional of the potential DT for the rolling mill 170;

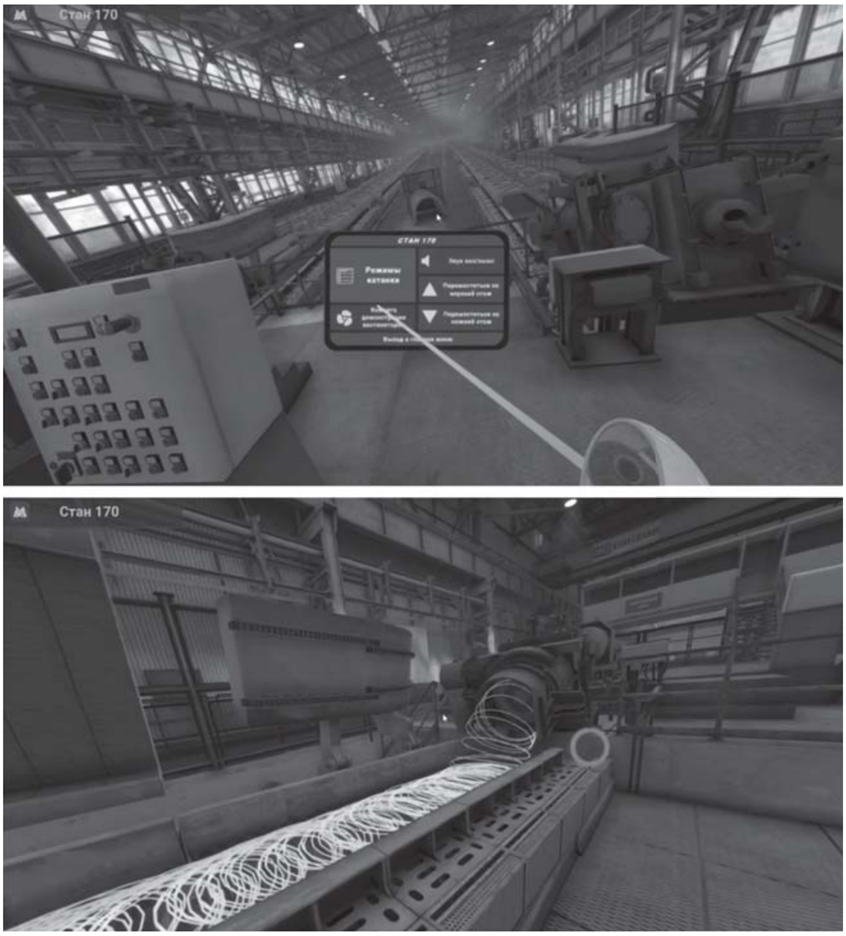

Fig. 7. VR interface of DT for the air cooling line of 170 rolling mill

- selection, adaptation and integration of all required mathematical models (**Fig. 8**);

- formalization (on the base of the concept and selected models) of all input and output data, which will be used by DT at the rolling mill 170;

- preparation of the task list to be solved in order to provide the models with required information flows (integration with the level 0 of ACSTP, obtaining of the data about a billet, access to the accounting system of rolling rolls etc.);

- forming of the complex dynamic mathematical model (CDMM), which calculates the main technological parameters of all processes (from transportation of billets to the storehouse and their heating to package and stenciling of the finished coils);

- conduction of calculating experiments on the base of collected and formalized data;

- organization of CDMM integration with the input data flow;

- evaluation of authenticity of CDMM operation (based on comparison of the calculated and practical data);

- development of interaction interfaces with the model (taking into account all requirements from production specialists) with planned creation of at least one classical interface for operators of the main operating control room;

- carrying out of evaluating and approval tests.

Several production effects, which are awaited after putting into practice of the rolling mill DT, are presented below:

- simulation of loading of the rolling stands drives in the rolling mill line and redistribution of forces in the case of overloading, taking into account vibration monitoring data, allows energy saving for resource of gear boxes, stand components and auxiliary equipment;

- simulation of the new, varied, boundary and actual operating procedures of the rolling mill and its pass designs allows cutting the expenses for putting into practice modified and new operating conditions;

- predictive analysis for forecast of rolled metal properties is based on analysis of the billet data, simulation of heating processes, simulation of rolling and cooling, analysis of the data on geometry and mechanical properties of rolled metal, neural network analysis of the data on raw materials (billets) as well as processes (rolling and cooling) and quality of finished rolled products (Hi-Profile and testing data from laboratories);

- potential prospect of DT integration with the level 2 of SCSTP (and higher levels) allows considering the problem of reducing harmful influence of the human factor on production results.

Let us consider several features of DT development prospects for the whole section rolling shop at MMK. Due to external political and economical situation, it is almost impossible to use various foreign software products for DT integration in general and more complicated system. At present time, the authors are not aware about any domestic platform for mutual integration of complicated digital twins of technological processes, which is practically used in metallurgy. From this point of view, the developing project (digital twin of rolling technological process at the section mill) can be considered as the experimental and pilot site for consequent domestic developments in these directions: both applying to metallurgy and in creation of digital twins for various technological processes. The problems of further researches in the field of integration of complicated DT can be examined at the stage of appearance of two and more operating DTs for technological processes, which are combined as a common line (e.g. DT of steel casting at continuous casting machines and DT of section rolling).

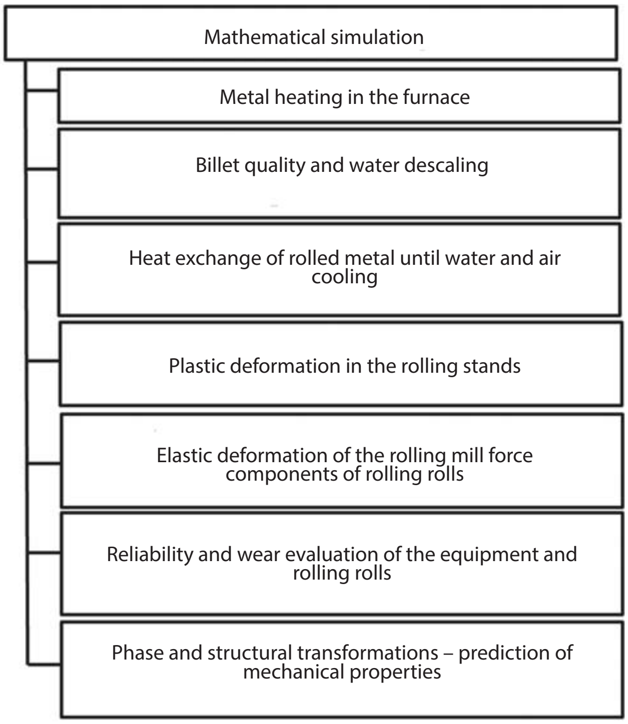

Fig. 8. List of the models for inclusion in DT of the rolling mill 170

Conclusion

The main applied solving task during creation of DT for the whole technological chain for manufacture of rolled metal at the section rolling mill 170 concludes in incorporation, adaptation and integration of the existing mathematical models and their connection with data sources (raw materials, technological processes, finished products) for maximally efficient use in solving the industrial technological tasks.

The potentially obtained product (DT) has no analogues in its functional (in section rolling) both in Russian Federation and abroad.

Efficiency and correctness of the chosen approach are confirmed by successfully realized digital twin of the air cooling line at the section rolling mill 170 of MMK with potential economic effect measured by tens of millions rubles, owing to exception of patenting processing at the following wire rod production stage.

In the case of successful implementation of DT for the technological process of rolled metal manufacture at the section rolling mill 170, the problem of development the self Russian platform for integration of complicated DTs within the framework of common system at metallurgical works can become actual.

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