The methodology of a locomotive simulation model development within the model-oriented approach

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Abstract. The use of mathematical modelling at the early stages of product design makes it possible to substantiate fundamental technical solutions, taking into account all possible (large number) requirements for the product by consumers and operation. At this (early) stage, it is important to use well-tested and convenient tools for designers to create virtual stands and digital twins (DC), confirming compliance, as well as forming the structure of systems and products as a whole. The article discusses a comprehensive methodology for the process of constructing a numerical model of a locomotive for analysing dynamics under various operating conditions. It is based on the top-level structural model (LBM), which is presented in the form of a block diagram and is used at all stages of product design. The required detailing of such a model depends on the actual tasks. The detailed models of the systems that have been developed within the framework of the work are presented.

1. Introduction
Mathematical modelling has long been an integral part of the design and development of new products. At the present stage of development of engineering activities, there is a process of combining methods of mathematical modelling and technologies of a systematic approach in the design of complex products. In connection with the development of computer technology and software, there is a natural interest in design based on a model-based approach [1], which allows to create a data centre at all stages of the life cycle of complex products.

The introduction of a model-based approach (MBA) in the design of complex systems allows at any design stage to assess the impact of various technical solutions on the functional characteristics of the project and choose the optimal ones [2]. Using this approach in sequential design can significantly reduce development time by eliminating the process of rework, rechecking and development of new prototypes by identifying errors and fixing them already at the conceptual design stage. The maximum number of errors in sequential design arises, as a rule, due to insufficient study of the requirements for the design object specified in the terms of reference, or their incorrect formulation.

In this regard, at all design stages, it is important to use convenient tools, specifically for design engineers, which are based on models with an appropriate level of presentation (design parameters and
physical quantities), while at the early design stages, models from the existing database can be used
previous projects, which reduces development time. Since a locomotive is a complex technical system
consisting of mechanical, electrical, hydraulic and other systems, the use of a model-based approach in
the design of modern locomotives allows in a relatively short time to create reliable machines with
optimal characteristics that meet numerous requirements.

This article proposes a comprehensive methodology for the process of constructing a computational
model of a locomotive for the analysis of various operating modes. The technique allows you to quickly
create various configurations of functional solutions in a single parameterized mathematical model, and
then use and refine these data at all stages of product design (with the required degree of detail). At the
same time, in the process of "development", the models of systems and units are interconnected with
adjacent ones.

2. Brief overview
Historically, most actively, advanced design methods developed in aviation and rocket and space
technology, since the cost of correcting design errors in these industries increases many times from stage
to stage (figure 1) [1-3]. Today, design methods are being developed in other industries, for example, in
the oil and gas and automotive [4-7].

![Figure 1. The relative cost of fixing design errors at different stages of development.](source)

MBA is actively used in locomotive building [8-11], along with the use of models of individual
systems [12,13].

3. The main part
When performing development work, as a rule, the following stages are performed:

- exploratory research;
- development of a technical proposal;
- development of a draft project;
• development of a technical project;
• development of working design documentation for the manufacture of a prototype;
• production of a prototype and preliminary tests;
• acceptance tests;
• approval of working design documentation for the organization of industrial (serial) production.

At each stage, an appropriate level of detail is required for the product being created. For example, at the stage of a draft design, data for simulation modeling is information obtained from the analysis of materials and results of previously created (similar) prototypes, as well as enlarged versions of schematic diagrams. At the WDD stage, there is already a specification for the equipment of the product being created, but there is not a sufficient test base. Thus, the detail of the models and the description of design features should be adequate to the design stage. The accuracy of the model and the associated complexity must be consistent with the goals the model is designed to achieve. Accordingly, at different stages of the product development process, different models are required both in purpose and in complexity.

Currently, the following trends in the development of locomotive systems can be distinguished:

• systems are becoming more complex and heterogeneous;
• systems are becoming more integrated, interdependent, mutually influencing each other;
• systems are becoming more mechatronic, with widespread use of active control systems and AI methods;
• functional software has a large amount of code that requires separate checks;
• use of cybersecurity technologies.

Considering the above, to create a mathematical model, the following technique is proposed, "conditionally" consisting of three blocks (figure 2):

• "Conceptual study" block;
• block "Systems development";
• block "Refinement of the model based on the results of physical testing".

Let's consider the blocks in more detail.

The "Conceptual study" block is one of the important stages in the beginning of the creation of a product using MBA, especially when creating a newly developed locomotive. It consists of three stages:
• creating a model of the architecture of product systems;
• building a functional top-level model;
• parameterizing the model with basic parameters.

At the stage of conceptual development, the architecture of the product is determined from the point of view of the main (basic) systems included in it, a structural model (enlarged basis) is built, which reflects the structure of the product, the composition of the incoming systems, information about their integration and communication (data exchange protocols) between them in accordance with requirements. The structural model is presented in the form of a block diagram (architecture), each input (output) is linked between all systems.

It is important to correctly determine the composition of the "enlarged framework" and work out the basic, basic connections between the elements of the structural model (interfaces). The composition of the structural model and the relationships between elements are usually determined by “prior design experience,” or TOR.

Figure 3 shows the developed locomotive architecture. The architecture is based on previous design experience and describes a "complete product", it contains blocks of typical models of systems and their connections (as part of the product), as well as external environmental conditions and load profiles. The developed architecture can be adapted for most locomotive models.

This architecture is the basis for creating a virtual integrated model, which is understood as a complex mathematical product MVA (skeleton), which includes numerical models of the main systems of the modelling object, in which interconnections and mutual influence of systems on the functioning of each other and on the entire object of modelling as a whole.

![Typical locomotive architecture](image)

**Figure 3.** Typical locomotive architecture.

A distinctive feature of the MVA is its configurability - the ability to replace one basic block of the top-level architecture with another, identical in purpose, number and type of connections with other blocks without losing the model's performance.

After creating the top-level framework, a primary generalized functional model is built. Functional models here mean computational computer models of MVA blocks.
Functional models are initially fully parameterized. That is, there is an automatic opportunity to change the characteristics of the system in the model by simply changing the value (or function) of one or another parameter.

The generalized functional model can have a variety of representations and details. From a set of analytical dependencies connecting "input" A "with output" B "to" enlarged ", at the level of the main units.

Block” Product systems development ". In the previous stages, we have already received the "first" simulation model. In this block, the required detailing is performed (depending on the stage of the development work). Detailing at this stage is understood as the construction of more detailed design models of the MVA blocks, in which the entire architecture of the system, including all incoming subsystems and aggregates, must be defined. System model detailing is an iterative process. Several alternative configurations can be considered, including those with different input equipment and for different tasks.

The elements of the MVA themselves act as "containers" that can be filled with different content depending on the design stage. For example, if a draft design is currently underway, then, accordingly, the "Frame" element will be described by analytical dependencies and simple numerical models. If this is the stage of release of the WDD, then this will already be a more detailed model of this block, but at the same time it will fit into this architecture and the rest of the system will not lose functionality.

All components (mathematical models of MVA blocks) that describe architecture elements are stored in the user library. At the same time, different versions of one component of the architecture are interchangeable, without losing the performance of the mathematical model. For example, one control system can be replaced with another, while all the graphics, dashboards and animations configured in the numerical model of the product as a whole will remain operational, and the settings of the numerical experiment itself will not fail. This function is very convenient, because even at the last design stages, the engineer needs to type a certain combination of product systems with the required degree of detail.

For example, in the design model of a product, it is necessary to take into account the component "Carts" in detail, while the other components of the architecture do not require such detailing; therefore, for "speed of counting" they can be described in a simplified form.

Thus, there is always a ready-made design model of the product, and all the developments obtained at the previous design stages are saved. At the same time, at the enterprise level, it is possible to fix the rules (certain regulatory documents) for creating a numerical model of the basic architecture and its components. With this approach, any employee of the enterprise with the appropriate competencies can work with previously created numerical models.

It should be noted that each element of the basic architecture can be used as a separate computational model.

The last block "Refinement of the model based on the test results" - checking the accuracy of the calculation and the correctness of building a simulation model.

As a software implementation of the methodology for constructing a mathematical model of a locomotive, it is proposed to use two types of software (figure 4):

- 1D simulation package, for example, MATLAB (simulink), Simcenter Amesim, PA9, etc. (these packages contain ready-made libraries of transmission, mechanics, hydraulics, control and monitoring systems, etc.). Moreover, modelling does not require CAD geometry files.
- This is where the structural model of the product is created and the interaction between the blocks is carried out;
- 3D modelling package, for example, Ansys, Simcenter 3D, Euler, Universal Mechanism, etc. (in packages, if necessary, it is possible to create numerical models of individual elements of locomotive systems with high detail, complexity and their further connection to the 1D locomotive model).
Some tasks require a joint solution (data exchange between software systems), it is necessary that these products provide support for the FMI interface.

**Figure 4.** Software implementation of the technique.

Figure 5 shows a "typical" structural model of a diesel locomotive, made in a 1D package.

**Figure 5.** Structural model (1D modeling package).

Initially, a product architecture (enlarged base) is created, consisting of blocks (figure 3).

The technology of transferring information between blocks is implemented according to the principle of storing all variables in unified storages according to the characteristics of links and the possibility of calling them in a separate block for the account of the supply to each block of the corresponding buses in which the incoming and outgoing signals go simultaneously. Several buses are allocated for a typical architecture: a bus with "signals" transmission; bus with information flow for modelling electrical components; a bus with a flow of information for modelling translational motion, a bus with a flow of information for modelling a heat flow; a bus with a stream of information to simulate rotational motion; a bus with a flow of information for modelling hydraulic circuits). Each element is mathematically described and parameterized.
Figure 6. Fragment of the block MVA - "Carts" (design model).

It should be noted that the "Carts" block (figure 6) is implemented using elements from the built-in library, in the future you can detail (if necessary) this system, even add new links, but the main links will remain, while the rest of the elements do not need to be redone. The block "cooling system" (figure 7), on the contrary, is described in detail in several configurations, in the future it can be detailed or simplified.
Figure 7. Fragment of the block MVA - "Cooling system", described using RM.

During the iterative process of models of systems in the MVA, a situation arises when it is no longer possible to qualitatively describe the model of the system using 1D elements, therefore, this component of the model is solved in a 3D setting and a joint 1D + 3D solution is carried out. In this case, the main part of the MVA is modelled in 1D, and individual components in 3D. It should be noted that the solution in 3D setting is time consuming. Therefore, they resort to using ROM models (low-order models) - in fact, this is a table with the results of many calculations of a 3D element with different boundary conditions, which will then be introduced into the MVA.

4. Results and conclusions
The possibility of using MBA to build a model of the upper level of a TEM10 locomotive, which can be used at all stages of design, is shown. The required detail of the model depends on the design stage and the required calculation. Application of the developed model and methodology in engineering practice makes it possible to carry out multivariate calculations and substantiate the fundamental technical solutions of the locomotive at the stage of conceptual development. It should be noted that the characteristics and purpose of this model meet the requirements for a TsD [14].

Within the framework of the project, a ROM model of the cooling system radiator (one of the elements of the “Cooling System” unit) (figure 8) was also developed in order to speed up the calculation process. The use of this approach makes it possible to take into account the design features of the designed geometry of the radiator as part of an integrated model for reproducing the operating modes of the product at sufficiently long-time intervals of modelling, without using high-performance computing power.
When using the MBA, the developer, moving from project to project, accumulates both computational models and refines them. As a result of such a "capitalization" of knowledge and experience, virtual functional modelling within the framework of each subsequent project requires significantly less time with an increase in the quality of design solutions. It is important that several engineers can be involved in the development of the computational model at the same time.

In the future, the development of the model assumes its validation and verification, after which the model can be used to build new modifications of TEM10, as well as to create new designs of locomotives. Some results of model validation and verification will be presented in a separate publication in 2022.

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