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## VERIFICATION OF A TRAIN ON RAILWAY TRACK SIMULATION AND OPTIMIZATION SYSTEM

**Summary.** This article presents a Train on Railway Track simulation model and program developed by the authors. The model implements the module for multiple-criteria optimization with a set of proposed objective functions allowing reductions in train passing time, total costs, energy consumption, and adverse environmental impacts. The Train on Railway Track simulator has been developed to allow both the simulation itself and the ride optimization. The main achievement is the development of an algorithm that simulates the passage of a train over 500 km, the duration of which did not exceed two minutes. We present an analysis of the impact of model changes on the duration of the simulation and the accuracy of the results obtained. This allows the use of these achievements in simulations carried out for the railway, automotive, or aviation industries as well. Changes in the classical approach to optimization proposed by the authors made it possible to obtain results directly by solving classical systems of equations. The change in the approach to the optimization and system algorithm has reduced the operating time of the optimization system from thousands of simulations to a single simulation with an additional optimization process that takes several minutes to calculate. This article is a continuation of the description of the work performed, and basic information about the developed simulation model and software functionality is included in a separate publication [13].

### 1. INTRODUCTION

Rail transport in Poland accounts for approximately 10% of passenger transport and over 30% of freight transport. This is also the most ecological of all transport types. Nevertheless, rail transport allows ride optimization in the aspect of energy consumption [1, 2], which is related to driving style, or in the aspect of time of the journey [3, 4]. It must be pointed out that energy savings are not only considered in the economic dimension but also in the ecological dimension [5] because they contribute to reducing greenhouse gas emissions and other forms of air pollution. For this reason, reducing energy consumption is a major objective of rail carriers, which is certainly predominantly related to the high costs of energy and their large share of the total budget.

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Methods to reduce energy consumption include eco-driving, which involves implementing driving techniques that minimize energy consumption while keeping the ride time stated in the schedule. Energy savings are also made possible by the optimization of the train energy cooperation [6].

For these criteria to be met, it is necessary to seek new technical and organizational solutions [7] while assuring the required safety level. The complexity of the rail transport system enforces the application of advanced numerical methods [8, 9] for solving engineering tasks, including modeling and simulations, followed by multiple-criteria optimization.

For a train ride to be modeled, the process must be defined, and then the knowledge must be transferred together with the parameters of railway stock technical specification. Furthermore, it is necessary to transform the modeling methods and optimization into numerical form so that the system can effectively support major decisions regarding rail transport management [10-12]. The Train on Railway Track (TORT) simulation system is aimed at the optimization of the entire transport process due to the defined objective functions and the option of using system assumptions in the working environment of a rail company.

This study presents a verification of the system not only from the point of view of functionality but also (and mainly) from the point of view of computation time.

In the case of scientific work, the time of several hours (or several dozen hours) of numerical calculations for the developed numerical model is acceptable, but in the case of commercial applications, it is a challenge to obtain a calculation time acceptable to the customer (i.e., a maximum of several minutes of calculations). Therefore, this article presents and tests the impact of changing the model and its calculation parameters (not the parameters of the modeled object) on the calculation time of the simulation module and the optimization of the train ride.

The classic approach presented in Fig. 1 (left side) assumes that the algorithm performed  $C$  simulations constituting, as a minimum, a set without repetitions of all combinations of input variables for a single train driving simulation (1).

$$C_n^k = \frac{n!}{k!(n-k)!}, \quad (1)$$

where:

- $C$  – total number of combinations (number of separated simulations) [-];
- $k$  – number of combinations from a given set (combination of selectable train running summation input values) [-]; and
- $n$  – number of elements (the smallest number of selectable input values for one train running summation) [-].

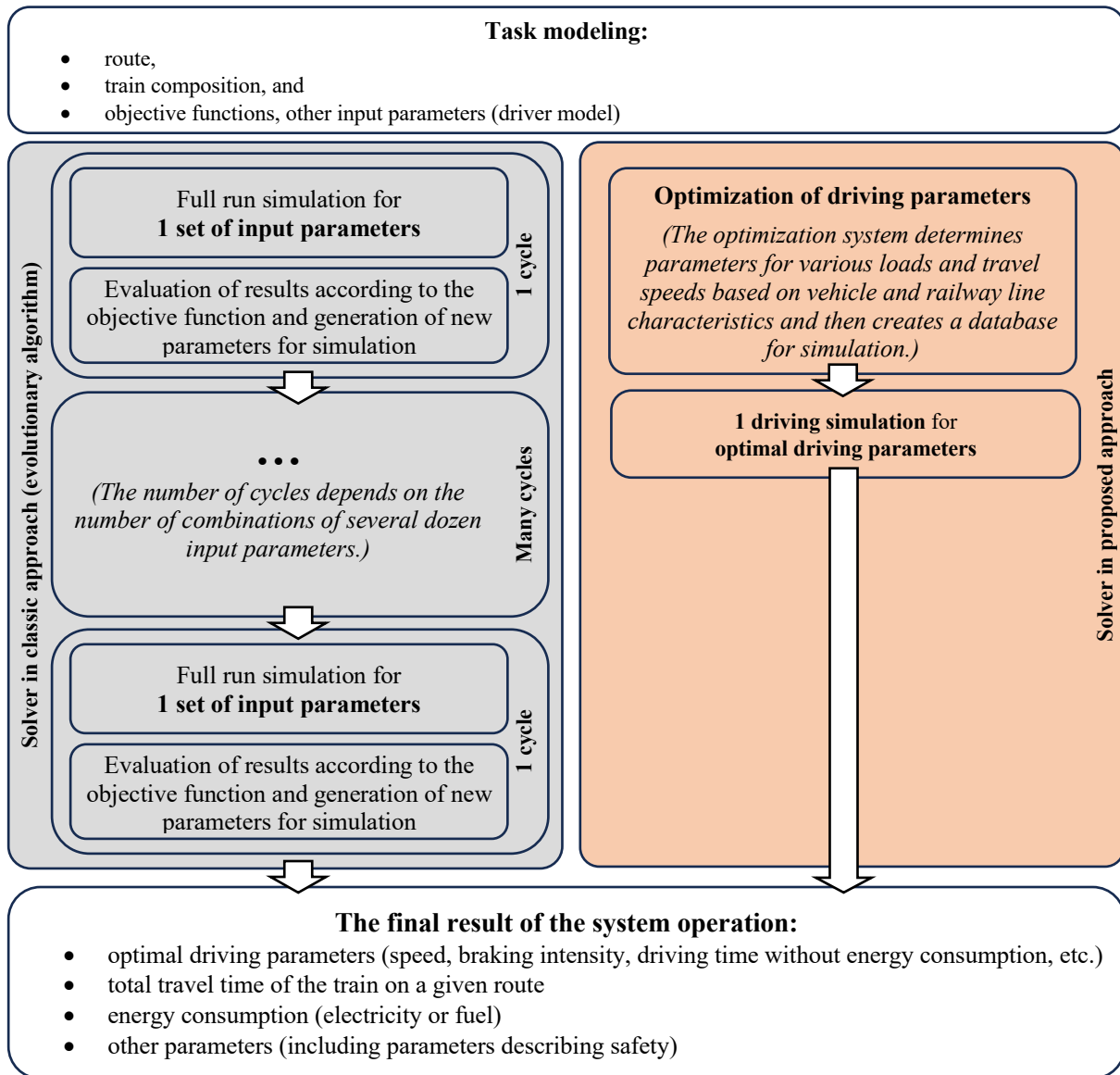
Linear input data should be discretized—for instance, speed in the range of, for example, 0-200 km/h to, for example, 100 intervals of 2 km/h—in order to significantly simplify the task (and, at the same time, reduce the number of combinations).

A similar approach (i.e., assuming 100 ranges reflecting values from 0% to 100%) will be applied to given power, braking intensity, running time without power, speed below the maximum value, deceleration before acceleration, and the way to coast after braking.

The input variables listed above are the most important parameters controlling the simulation (input data), but the list presented above is not exhaustive. This means that the number of combinations is  $n=100$ , and the number of combinations from a given set is  $k=7$ . This gives a total number of combinations (number of separated simulations)  $C=1.6 \cdot 10^{10}$ . Assuming that the average time of a single simulation is 10.8 seconds, the total simulation time of all combinations would be  $t_s=4.8 \cdot 10^7$  h. This means that checking all combinations of input data is practically unjustified. Even if the number of intervals was drastically reduced from 100 to 20 (e.g., for a speed of 10 km/h), the simulation time would be  $t_s=233$  h. For each of these simulations, an evaluation of the objective function and recording of parameters will be carried out. The number of combinations can be reduced by optimization methods.

The authors, who have experience in the use of evolutionary algorithms, implemented this optimization method to search for the optimal solution. This method did not bring the expected results due to the very slow convergence to the optimal values. In the next approach, gradient method optimization was also used, but no simulation time was obtained that could be accepted and implemented in operational conditions in rail transport. The above analysis shows that the classical approach to

optimization through simulation evaluation should be abandoned in favor of a new approach in order to obtain an acceptable system uptime.



**The final result of the system operation:**

- optimal driving parameters (speed, braking intensity, driving time without energy consumption, etc.)
- total travel time of the train on a given route
- energy consumption (electricity or fuel)
- other parameters (including parameters describing safety)

Fig. 1. Scheme of changing to the new approach in solver from the multiple simulation model for parameter optimization to multi-criteria optimization and a single final simulation

The new approach assumes that one simulation is performed but for the previously determined optimal input data (Fig. 1, right side). Only after a complete change of the concept of the system should an analysis of the influence of the individual parameters of the simulation run on the computation time be carried out.

## 2. SCOPE OF THE WORK AND METHODOLOGY

The development of computer software involves several phases, from the conceptual phase and physical, mathematical, and numerical models, through coding and the verification of the final version. Coding certainly involves continuous testing, but this sort of test is usually done to verify a selected code fragment and is not equivalent to functional, efficiency, integration, or utility testing. Therefore,

final tests form a major element of the train ride simulation and optimization system, as well as accounting for any adjustments to be made.

The first phase of testing took place as early as during the conceptual phase and mathematical model construction, as well as the development of the preliminary version of the software. The tests soon revealed that the classic approach to optimization involving multiple simulations (thousands and more) of the train ride on the same route but for different input data and ride parameters would not allow industrially acceptable times of numerical calculations to be achieved.

Therefore, after such tests were performed, a decision was made to change the model and the structure of the optimization system and to replace them with ride parameter optimization followed by a single simulation of the ride.

Pursuant to efficiency tests, it was confirmed that this approach shortened the time of numerical calculations by several orders of magnitude, namely up to several minutes. Efficiency tests have also evidenced that the mode of the full visualization of parameter changes during simulator operation significantly elongates the operating time of the software, while the imaging of such data is not required for the end user; therefore, this option was left for testing purposes only. Owing to this change, we achieved a further, approximately nine-fold, acceleration of software operation.

The aforementioned tests have been divided into utility tests, efficiency tests, and functional tests accounting for the optimization module.

Efficiency tests accounted for the impact of route length; the number of locations passed through, including stops; average and maximum train speeds; the number of wagons modeled in the train; and the impact of simulation lag during numerical calculations.

Basic test data for efficiency tests included:

- route length (1, 10, 20, 30, 50, 75, 100, and 500 km);
- number of locations passed through (one, five, and 10, as well as a direct route);
- maximum train speeds (10, 40, 60, 100, and 160 km/h);
- number of cars (locomotive and one, two, three, five, 10, 20, and 40 wagons, as well as locomotive alone); and
- simulation step (0.1, 0.5, 1, 5, 10, and 20 s).

Batch files were developed for the above test data, and the results were verified. The main parameter verified in this case was the calculation time. No functional errors were found at this phase because the verification was performed at an early phase of system functional tests. Any utility changes to improve system operation were implemented in parallel with efficiency tests because they did not introduce changes to the numerical calculation time of the simulation and optimization system but only reduced the system preparation time, including the modeling process.

Functional tests of the simulation and optimization module involved the development of three test kits of 12 scenarios each. The tests were to allow comparative verification of the achieved optimization results for equivalent criteria.

The number of test combinations was limited by selecting a set of basic input variables, namely:

- Trainset:
  - locomotive (engine only) – minimum weight;
  - trainset of a medium weight (assumption of 20 wagons, loaded); and
  - trainset of maximum weight (assumption of 40 wagons, loaded).
- Route:
  - short – no intermediate stops – 20 km;
  - medium – with stops – 184 km (Katowice–Wrocław); and
  - long – with stops – 560 km (Katowice–Gdynia).
- Optimization type:
  - no optimization – reference – medium profile;
  - minimized time of the ride;
  - minimized energy consumption;
  - minimized costs of the ride; and
  - minimized complex function.

➤ Maximum speed on the route:

- minimum – 20 km/h;
- medium – 60 km/h; and
- maximum – 120 km/h.

The ride simulated during software tests was executed using the route without detailed changes to the parameters along the entire route. Trainset, or actually its weight, forms one of the major factors affecting the time and costs of the journey. In Poland, the maximum trainset weight is usually 2000 tonnes, with the highest weight on record being 3335.75 tonnes (on March 5, 2021). Thus, it was justified to test the entire range of typical operational loads, namely from zero (engine only, 118 tonnes) through 2000 tonnes, with an intermediate value of 1000 tonnes.

Therefore, three test kits were developed:

- Test kit No. 1: Diesel freight locomotive ST40 (311D) only, weighing 118 tonnes;
- Test kit No. 2: Diesel freight locomotive ST40 (311D) and 11 loaded coal wagons, weighing 1035.4 tonnes in total; and
- Test kit No. 3: Diesel freight locomotive ST40 (311D) and 23 loaded coal wagons, weighing 2036.2 tonnes in total.

The basic parameters verified during the functional tests involved a comparison of the optimization results for the predefined objective with the optimization results obtained for another objective or for the simulation with no optimized parameters. A precise comparison of the simulation and optimization results with actual values was beyond the scope of this phase of the works and would have been difficult due to the simplified route definition applied here. Nevertheless, it can be stated that the obtained nominal ride times are similar to the actual values. Furthermore, it was also assumed that the system verifies gross errors in the obtained simulation results—namely, it defines the ride time for maximum train speed and compares it with the ride obtained. This eliminates the option of yielding trivial results to the user without notification.

### 3. RESULTS

As a result of the analyses, it was stated that the simulation module contains several dozen settings of task modeling, including the selection of wagons in the trainset, track modeling, and a choice of operator profile. Therefore, an option was provided to perform a task defined in the file and to start a task predefined in the software.

The software also accounts for the interface between the TORT2 software and the superior modular railway management system software.

Irrespective of the predefined settings or the choice of task definition file, it was decided that databases would be introduced with defined traction vehicles, wagons, or multiple units, together with their necessary parameters, to accelerate the modeling process. This allowed us to select the vehicles or modifications thereof at the time of modeling.

Furthermore, notwithstanding the above, it was determined that rail transport largely uses defined trainsets (e.g., Polonia, Chopin, Albatros), so the program also includes the functionality of defining, saving, and reading typical trainsets (Fig. 2).

Settings for the simulation itself require databases to be downloaded and verified. For this reason, first of all, the system tests database integrity and verifies and calculates the defined vehicles, trainsets, operator profiles, etc. Any missing data or nonconformities with the defined template cause the automatic display of an error message at the software start stage. After the message is displayed, the tree (Fig. 2, left side) automatically drops down, with missing components highlighted in red.

The presented change to the optimization system allowed us to reduce the calculation time needed for several thousand separate simulations controlled with an evolutionary algorithm to one optimization of the driving parameters of the simulator. This change of approach to optimization and the system algorithm resulted in reducing the system operating time from thousands of simulations (determined number  $C$  of simulations and the time required to run the simulations -  $t_s$ ) to a single simulation with an additional optimization process that takes a few minutes.

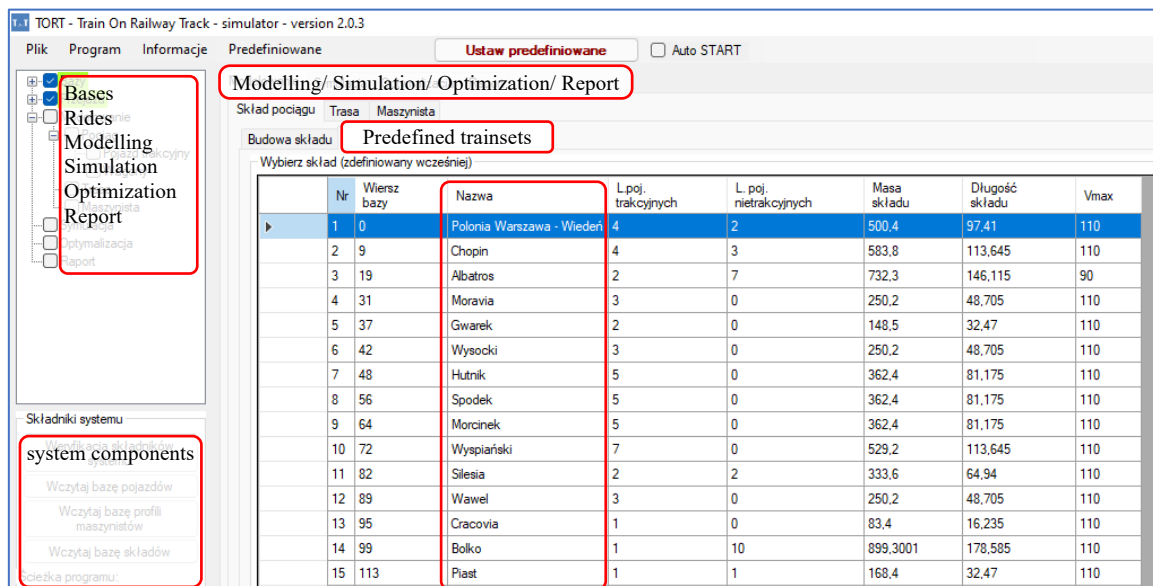


Fig. 2. View of the modeling module tab with a selection of typical predefined trainsets (original markings)

After a new optimization approach was introduced, the standard simulation process calculation time ranged from two minutes to 25 minutes, depending on the analyzed test data, which extended to as much as 40 minutes in the case of the longest route. However, it must be pointed out that with the real-time view turned off, the calculation time is only 4.5 minutes. Thus, as mentioned before, it is possible to significantly accelerate the operation of the simulation module nine-fold by turning off the real-time view of the system operation. In such a case, simulation results can be observed only after process completion. Observations made during simulation module operation are justified during software testing, but it is not indispensable to the end user. It is also possible to select an intermediate option, namely, to display simulation results at intervals defined in the software, defined in seconds. Further acceleration of the operation can also be achieved by turning off the active view of results on many diagrams; the software provides this option.

The changes to the system structure have allowed us to significantly accelerate the time needed for input data entry owing to the option of selecting predefined vehicles, trainsets, routes, and operator profiles, as well as to significantly shorten the time spent waiting for simulation and optimization results, which has not affected the quality of the simulation but has significantly improved the use of the software. Quantitatively, the time needed to obtain the simulation and optimization results was reduced from a value unacceptable to the user ( $C$  – number – thousands of hours) to a maximum of five minutes of optimization for routes in Poland in the mode with the real-time view turned off and when using the required hardware. The system was tested on a computer with a 64-bit operating system, with a processor: Intel(R) Core(TM) i7-8700 CPU @ 3.20 GHz with 12 threads, 16 MB of RAM, and an SSD.

For example, the route of 25 km in a strongly urbanized area, namely Katowice – Strzelce Opolskie, takes 122 seconds with the full real-time view and 13 seconds in the mode with the results displayed after the simulation is completed.

The tests indicate that the simulation of a ride with an average speed of 100 km/h on a 500-km route without intermediate stops takes 60.1 seconds for calculations. Adding intermediate stops of at least 20-60 seconds causes the simulation time to increase only by 2.0-4.4%. The analysis clearly shows that the requirement to optimize the system architecture and the applied calculation algorithms accounting for time limits, including the straightforward requirement not to exceed 180 minutes of calculations, has been fully met. The obtained results for TORT2 software clearly indicate that the optimization with the required ride simulation at a rail track in Poland will take about five minutes of calculations while using an average PC computer. Moreover, owing to the harmonization of the data exchange system, the task can be defined either in TORT2 software or in a superior system and automatically be downloaded to the simulation.

The analysis also involved a change to the number of stops, length of the route to be covered in the simulator, the number of locations passed through, train speed, and the number of wagons in the trainset. For this purpose, an input data kit was developed for the TORT2 system, as described in Chapter 2.

First, test programs were developed with respect to the verification of route length affecting calculation time. Simulator ride time was measured at the route lengths of 1, 10, 20, 30, 50, 75, 100, and 500 km. The simulations were made for identical trainsets, namely one locomotive plus five loaded freight wagons. The ride assumed an average speed of 100 km/h with observed dynamics of acceleration at the starting point and braking at the target destination. The tests confirmed the correctness of simulation calculations from a physics perspective. It was checked that, on the route of 500 km for maximum speed (average speed, considering just the start and stop and relatively long ride) of 100 km/h, the simulated journey time amounted to five hours, three minutes, and 44 seconds (10:00:00-15:03:44). Considering that the train moves with an average speed of 100 km/h (except for during acceleration and braking), the journey takes exactly five hours. Thus, there are an additional three minutes and 44 seconds. By deducting the stoppage time at the starting point and end point ( $2 \times 60$  s), we gain an additional time of 104 seconds, which constitutes 0.5% of the total time of the journey. The time, however, does not constitute a calculation error but results from the need to accelerate the train from a standstill after leaving the starting point to the speed of 100 km/h and braking at the endpoint station.

The analysis of TORT2 efficiency test results reveals that calculation time is approximately linearly dependent on the train route length. The dependence is visible both for calculations with the real-time view of changes to all the parameters during the online simulation and for calculations with results displayed offline after the process is complete. According to the predefined test program, journey time is increased by the time of the simulated stoppages at the starting point and end point stations, namely  $2 \times 60$  s (Fig. 3). The analysis clearly shows that the TORT2 calculation time is fully acceptable to end users. It must be stated that the simulation of the exemplary journey of 100 km took just 10.7 seconds, while for the route of 500 km, it took 60.1 seconds. The times can be reduced further if stationary computers of average or high quality are used.

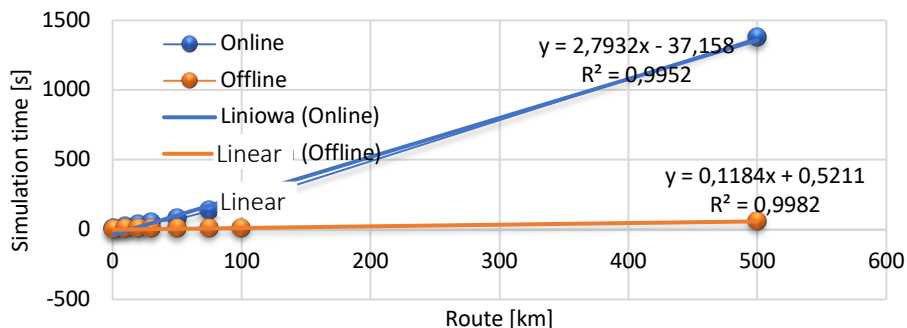


Fig. 3. TORT2 calculation times in the route function (online/offline)

- **Analysis of the impact of the number of locations passed through (zero, one, five, and 10) on numerical calculation times**

The analysis of the impact of the number of locations passed through on simulation time involved the route of 100 km, for which simulation time was measured exclusively for the ride from starting point to end point stations, while afterward, locations passed through were added in the quantities of one, five, and 10. It must be pointed out that the waiting time at the starting point and end point stations was set as 60 s, while the stoppage time at intermediate stations was 20 s. The obtained simulated journey time with five intermediate stations was 10:00:00-11:07:12. The calculations indicate that, when we deduct stoppage times ( $2 \times 60$  and  $5 \times 20$  s), we elongate the journey time vs. calculations for the average value of 100 km/h by 212 seconds. The time is necessary for train acceleration and braking due to passing through intermediate stations (Fig. 4).

When analyzing the obtained results, we can state that the addition of locations passed through elongates the average calculation time by 2.0% for online simulations and 4.4% for offline mode. Evidently, the impact of the number of intermediate locations/stations is lower than the linear increase of calculation time with changed route length. It must be pointed out that, in this case, locations passed

through indicate the need for stopping, waiting for 20 seconds, and accelerating again to the traveling speed. This causes an insignificant elongation of the journey time related to train dynamics and, thus, affects calculation times by 2.0-4.4%. Intermediate locations passed through without stopping do not affect journey time or the calculation time in TORT2 software.

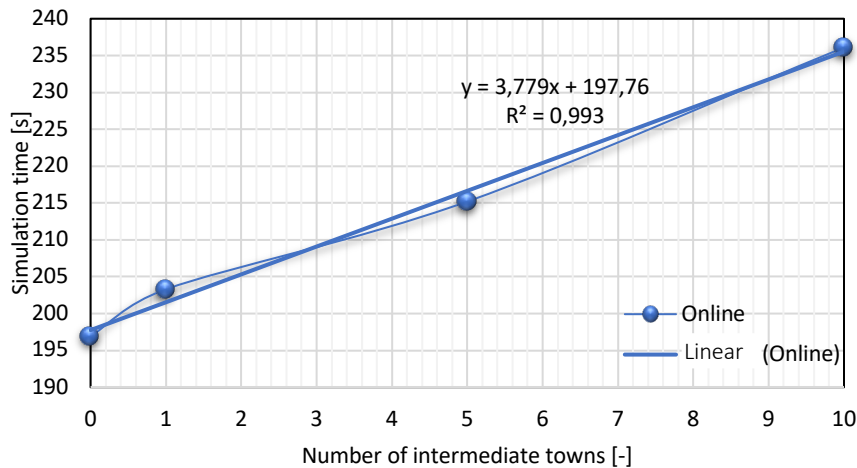


Fig. 4. TORT2 calculation times in the locations passed through function (online mode)

- **Analysis of the impact of train speed (10, 30, 50, 100, 160, and 200 km/h) and the impact of simulation time step on the numerical calculations time**

When analyzing the impact of average speed, the applied scenario involved an ST40 (311D) locomotive plus five loaded wagons. The route had a length of 50 km.

Pursuant to the simulations, it was determined that speed is of major importance to journey time, namely simulation length and, thus, calculation time. The lower the speed, the longer the journey time. Therefore, the simulation of a freight train journey will presumably require a longer calculation time compared with a simulation of a passenger train journey. It can also be estimated that the simulation of one hour of trainset journey takes about 10 seconds of calculations with a calculation time step of 1 s (and 1.5 s with a time step of 10 seconds). The longest calculation times were obtained for the lowest average speeds. A much longer calculation time, compared to the speed of 30 km/h, naturally results from the physical dependence of journey time and from the relatively low resources of the computer used for the tests (8 GB RAM). When comparing results obtained in the online mode (Fig. 5) and offline mode (Fig. 6), one can observe a similar exponential reduction in calculation time with an increase in average speed. Therefore, apart from introducing offline mode, this is the major value affecting the calculation time. One must, however, remember that the average speed for most tasks required by the end user will be the resulting element, whereas the dependence of the speed on the calculation time ensures that even the longest journey can be simulated in an acceptable time.

It is possible to further reduce calculation time by extending the numerical calculation step (e.g., from one second to five or even 10 seconds). This is particularly favorable if the train travels at a constant speed because dynamic changes in this step are the lowest.

The option of changing the time step of the simulation from 1 s allows us to simulate the train journey along the 500-km route at an average speed of just 10 km/h at a time not exceeding 13,947 seconds (almost 4 h for online mode) to 8.4 seconds for a time step of 10 s (offline).

- **Analysis of the impact of the number of wagons in the trainset on numerical calculation time**

The simulation was performed for a locomotive ST40 series – 311D – with loaded Eanos 423W coal wagons. The numbers of simulated coal wagons were zero (engine only) through one, two, three, five, 10, and 40 wagons. The route length was 100 km, and the maximum speed was 60 km/h.

The results presented in Fig. 7 show that the train weight relative to the number of wagons in the trainset does not critically affect the calculation time. The diagram in Fig. 7 shows a 20% increase in the calculation time in online mode (21% offline) for 40 wagons vs. engine only, but the differences are



related to the need for longer acceleration and braking times for the trainset, which translates to a longer calculation time in the simulation.

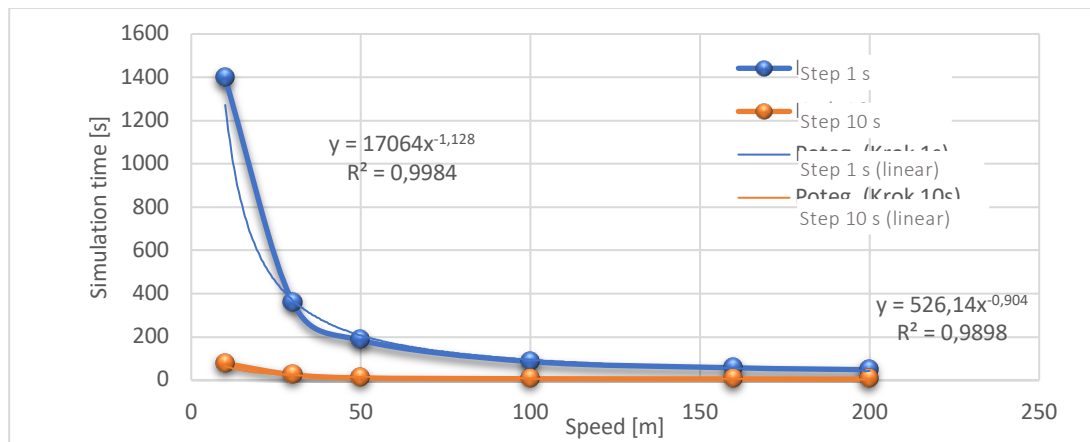


Fig. 5. TORT2 calculation time in the average speed function (online mode)

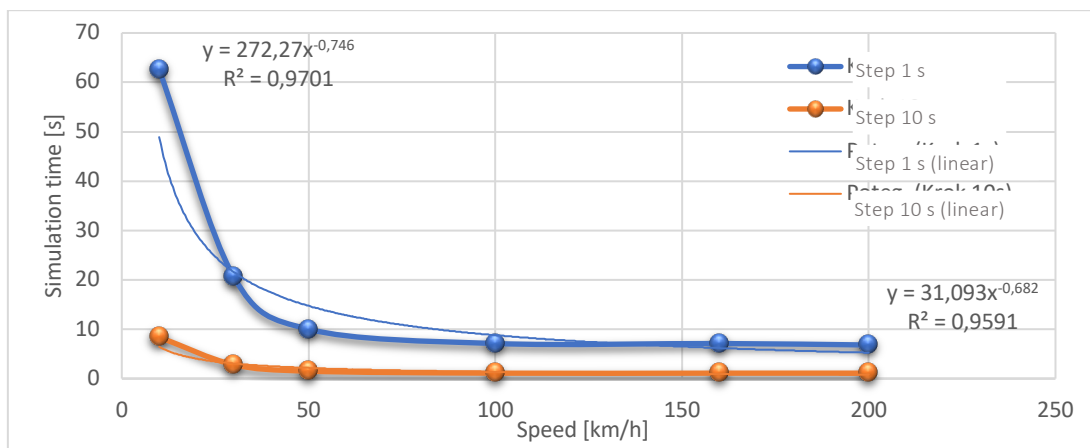


Fig. 6. TORT2 calculation time in the average speed function (offline mode)

• **Analysis of the impact of simulation time step on the numerical calculation time**

The tests revealed that the simulation of the ride of 50 km with a speed of 10 km/h takes 1394.7 seconds online for a 1-s time step; after changing the time step to 10 s, it is shortened to just 77.4 seconds, which is an over 18-fold time reduction. Detailed analysis of calculation time step impact has been performed for the 20-km route and the speed of 100 km/h. The test train comprises a locomotive of the ST40 series – 311D – and five Eanos 423W coal wagons.

The analysis of test results and the diagrams drafted on its basis (Fig. 8) indicates that calculation time is an exponential function of the simulation time step. The approximation of the exponential function is relevant both to simulations made online and offline (Fig. 8).

In TORT2 software, basic settings involved the simulation time step (integral step) of 1 s. When comparing calculation time with the precision of keeping the train’s speed constant, it can be stated that the choice is a compromise between acceptable calculation time and the assumed maintenance of train speed. For the step of 0.1 s, the simulated speed is close to constant (it changes within the range of 100 to 100.1 km/h), but the simulation time is much longer than when the step is 1 s or higher. On the other hand, excessive increases in the calculation step, even up to 20 s, allow us to achieve a much shorter calculation time, but train speed (simulation of the engine-only scenario) changes in this case from 100 to 111.6 km/h—namely it is periodically higher by 11.6%. For some tasks, in particular, those including very long journeys, such changes could be acceptable (a lower maximum speed threshold can be set in the program), but due to the option of offline operation for much higher accuracy of the simulation (e.g.,

for the step of 1 s), there is no need to select a calculation step higher than the standard setting in TORT2 software, namely 1 s.

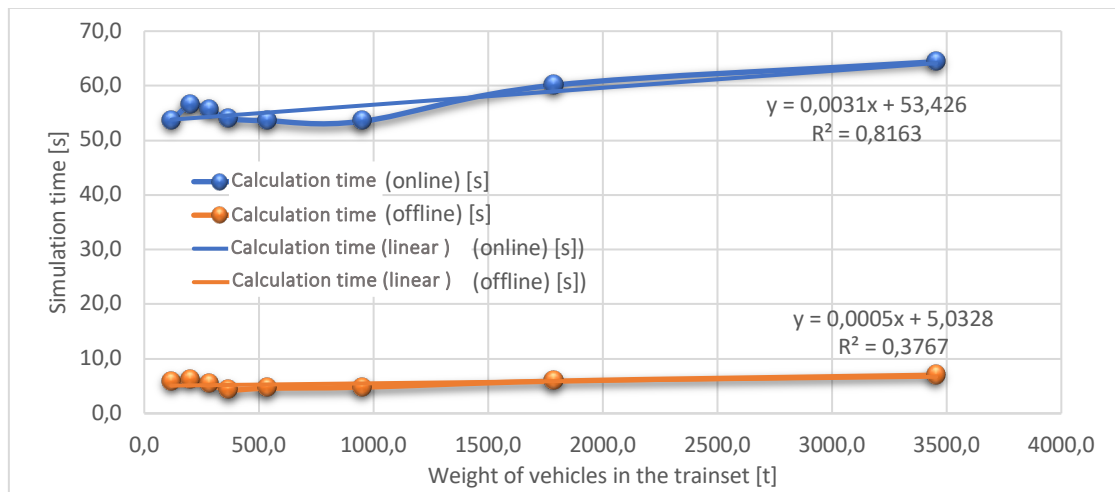


Fig. 7. Impact of trainset weight (number of vehicles) on simulation calculation time

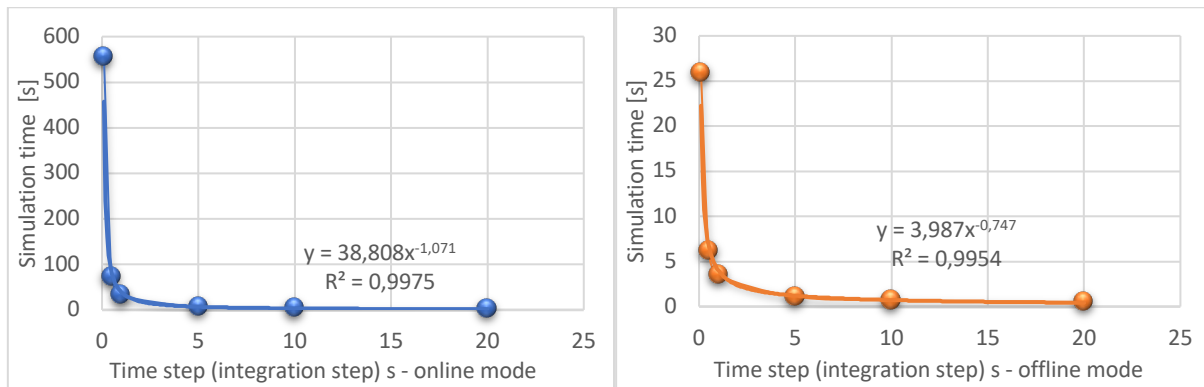


Fig. 8. TORT2 calculation time in the simulation time step function

Velocity charts for various time steps in the simulation are presented in Fig. 10. Speed fluctuations for the simulation step (engine-only scenario) of 1 s ranged between 98.9 and 100.3 km/h, which is a difference of approximately 1.4%. It must be pointed out that the indicated value of 1.4% does not constitute a numerical calculation error (this is several orders of magnitude lower due to the integration using the Runge-Kutta 4<sup>th</sup> order method) but is the time between which the simulator cannot react to the change of speed. During the actual journey, such fluctuations occur to a much greater extent in the case of driving using a speed control device (new vehicle types) than in older vehicles where the speed is controlled through the controller settings. For the operator, the priority for train driving is not as much to keep minimum speed ranges at the level of single km/h as it is not to exceed the speed limit applicable for a given track section. Therefore, the optimization process (safety priority) allows for accounting for this property by lowering the maximum speed by a defined value. One who wishes to obtain minimum values of simulated speed deviation from the average value while preserving an acceptable calculation time may select a simulation step of, for example, 0.1 s and offline mode, which, for the test performed, yielded a calculation time of 25.9 seconds. The results of the analysis indicate that the most important parameters affecting calculation time are the route length and speed, as well as the calculation time step. However, it must be pointed out that the impact of route length on calculation time is approximately linear. The impact of speed is due to the fact that the calculation step has its own time domain (e.g., 1 second), which is why driving at a higher speed naturally causes a longer route to be covered during a single step of the simulation.

The impact of the number of stops on simulation time does not result as much from their number as from the need to reduce the speed and the stoppage time. The simulator performs calculations during the stoppage to a limited extent (no drive dynamics), but each time step is calculated, and the set of conditions is verified (e.g., simulation complete, last stop, time for restarting the ride). Therefore, considering the actual density of the stops with respect to the number of kilometers to be covered, it can be stated that the impact of the number of stops on calculation time is marginal.

#### 4. DISCUSSION

To conclude, pursuant to the more than 76 full tests that were performed, it was determined that the calculation time is fully acceptable to the end user; in the offline mode, it did not exceed 62.6 seconds for the standard simulation time step of 1 s. The average test calculation time in the offline mode totaled only **10.8 seconds**.

The major factor allowing the achievement of an acceptable calculation time in TORT2 software was the conceptual change of the optimization process from multiple iterations and the selection of the best option to multiple iterations of ride parameter selection and a single simulated ride. Another element significantly reducing calculation time was the option of TORT2 operation in the mode where results are visualized only after a full simulation is completed, referred to as “offline” here. Depending on the route, this option reduces the calculation time from nine-fold to 23-fold (e.g.,  $1394.7 \text{ s}/62.6 \text{ s}=22.7 [-]$ ), whereas the most favorable time reduction is achieved for rides with long calculation time, which is particularly beneficial to the end user.

The next element to reduce calculation time selected and verified for achieving the most favorable system solution is the time step of calculations (integration step). As presented in Fig. 8, this parameter causes an exponential dependence of calculation time on reducing the simulation time step. Considering Fig. 8, as well as the impact of the calculation step on preserving constant speed in the simulator (Fig. 9), the integration step of 1 s was selected. Certainly, apart from this integration step, the applied the Runge-Kutta 4<sup>th</sup> order method introduces four additional sub-steps of calculations related to the numerical integration of the equations of motion, which contributes to improved simulation accuracy.

Speed is another element important to the simulation module operation time. Speeds within the range of 10 to 200 km/h were analyzed. Speed reduction affects simulation time in an exponential manner. Average speed is of major significance to simulation time, particularly if it is lower than 30 km/h (Fig. 5). Journey simulation time with a speed of 10 km/h was 10-fold longer than with a speed of 100 km/h. At the same time, the calculation time for the speed of 100 km/h was only 4% longer than the calculation time for the speed of 200 km/h. Further increases in the average speed of the ride below the indicated 30 km/h is of a lesser significance to calculation time in TORT2. This also means that for passenger carriers, where speeds are higher, hardware will be of lesser significance to the utility properties of the system than in the case of freight carriers.

TORT2 efficiency tests have revealed that calculation time is characterized by the linear relationship to the route to be covered by the trainset. The dependence is visible both for calculations with the full real-time view of changes to all the parameters during the online simulation and with results displayed after the calculation is complete (i.e., the offline simulation) (Fig. 3).

The analysis of the obtained results (Fig. 6) indicates that the addition of intermediate stops elongates calculation time by 2.0%, on average, for online simulations and by 4.4% for offline simulations. Thus, one can see that the impact of intermediate stations/locations passed through is relatively low compared to the linear increase in calculation time caused by the change in track length. It must be pointed out that, in this case, locations passed through require stopping, waiting for at least 20 seconds, and accelerating again to the target speed. This causes an insignificant elongation of the time of the journey related to vehicle dynamics and, thus, affects calculation time by 2.0-4.4%. Locations passed through (but not stopped at) do not affect the time of the journey or the calculation time in the TORT2 software.

The weight of the trainset was tested by a ride involving only an engine, followed by the addition of up to 40 loaded coal wagons. Pursuant to the tests performed, it was determined that this parameter does not significantly affect simulation time. Of course, considering the traction characteristics of vehicles, the dynamics of a vehicle weighing more causes longer trainset acceleration and braking times, which

is reflected in the simulator operating time, but the difference in calculation times between the engine-only case and a trainset of 40 wagons totaled 20% (21% offline). The tests also allow us to estimate that the simulation of a one-hour ride of a trainset takes about 10 seconds of calculations with the time step of 1 second.

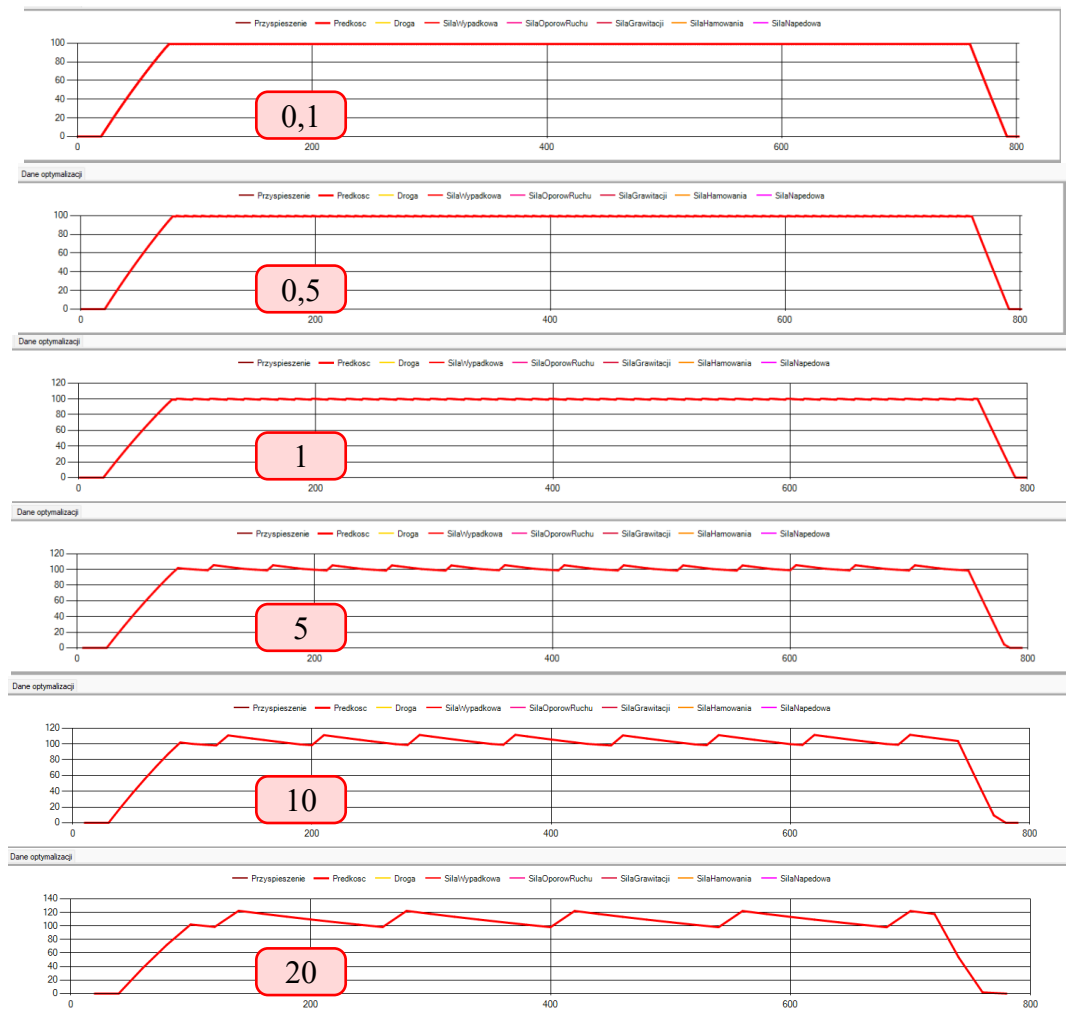


Fig. 9. Velocity charts for different time steps in the simulation – from top: 0.1, 0.5, 1, 5, 10, and 20 s

To conclude, the analysis of the research involving over 76 separate tests has confirmed the correctness of the adopted system architecture and start parameters for the simulation, which clearly confirms the achievement of the assumed system parameters from the end-user point of view.

To verify the correctness of system operation, first of all, three different kits of input data and 12 test scenarios were developed. Within verification works, the testing program was developed for over 76 tests involving changes both to the routes and various trainsets with differing traction parameters and wagon quantity. The trainsets were analyzed for various operator profiles. The verification also involved the impact of offline mode or changes to the structure of the simulation and optimization system. Within the framework of the tests, input parameters were also changed, including the integration step. The analysis involved the impact of average speed, the number of locations passed through and stopped at, as well as the impact of trainset weight, or the number of wagons in the set, on TORT2 operation time.

The presented number of changes to input data yields a significant number of test combinations. Therefore, a major part of the verification was performed each time during the algorithm implementation in MS Visual Studio 2019, with the final verification constituting confirmation of prior partial tests.

Furthermore, apart from the presented efficiency tests, functional and quality testing of the optimization module was performed, the results of which (due to the high volume of the analysis) will be presented in a separate publication.

When analyzing the obtained test results, it must be stated that both in the qualitative approach and in the quantitative approach, a significant improvement to TORT2 functioning has been achieved, both in the area of modeling and simulation and in the process optimization with respect to the previous software version (TORT1).

From a qualitative perspective, it must be stated that the changes to the system structure have allowed us to significantly accelerate the input data entering time by allowing the selection of predefined vehicles, trainsets, routes, and operator profiles and to significantly shorten the time of awaiting the result of simulation and optimization. From a quantitative perspective, the time needed to achieve simulation and optimization results was reduced from a value that was unacceptable to the user (thousands of hours) to a maximum of five minutes per journey in Poland in the mode with the real-time view of the simulation results turned off and with basic hardware provided. It must be pointed out that the average calculation time during the tests totaled 10.8 seconds, with a maximum time of 62.6 seconds.

This allows us to state that an acceptable (62.6 seconds vs. the adopted limit of below 180 minutes) TORT2 calculation time has been achieved, which also confirms the achievement of an acceptable result from the end user's point of view.

## 5. CONCLUSIONS

As a result of the analysis of the tests, it was determined that TORT2 meets the defined requirements and performs the functions assumed for all the defined modules, namely modeling, simulation, and optimization. Regarding the aspect of quantitative data, it is determined that the time needed to achieve simulation and optimization results has been reduced from a value unacceptable to the user (thousands of hours) to a maximum of approximately 45 minutes in the mode with the real-time view of the simulated ride in the territory of Poland. At a further phase of the works, a further reduction to just five minutes per ride was achieved with the mode with real-time view turned off and with the required hardware provided. The optimization task takes a few minutes of calculation on average in the mode without real-time visualization of the calculation, and, as a process, it is performed once (the process certainly includes many iterations).

The most important elements that allowed us to reduce the simulation time:

- replacement of optimization based on a classical approach—multiple simulations of driving on the same section but for different input data—to identify the optimal driving parameters for determining the optimal driving parameters using a numerical solution of a system of equations representing, for example, a combustion model and a single simulation with optimized driving parameters—time reduction calculations from thousands of hours ( $C$  number of repetitions with time  $t_s$ ) to hundreds of minutes of calculations;
- enabling the simulation to be performed offline (without constantly refreshing changes); and
- optimization of the simulation time step (not the integration step) based on the curve (Fig. 5) and the analysis of their impact on speed (Fig. 9).

Based on the presented changes for the optimization approach and simulation parameters, the average test calculation time obtained in the offline mode is only 10.8 seconds.

The system operation process has also been minimized to the selection and possible modification of predefined groups of input data, always with an option to change all detailed input data. TORT2 has also been adapted and incorporated within commercial system software, which also reduces the program's operation time to the necessary minimum.

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