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Article

The Assessment of Energy Efficiency versus Planning of Rail Freight Traffic: A Case Study on the Example of Poland

Piotr Gołębiowski [1,*], Marianna Jacyna [1] and Andrzej Stańczak [2]

[1] Faculty of Transport, Warsaw University of Technology, 00662 Warsaw, Poland; marianna.jacyna@pw.edu.pl
[2] PKP CargoTabor Sp. z o.o., Management and Production Planning Office, 02021 Warsaw, Poland; Andrzej.Stanczak@pkpcargotabor.com
* Correspondence: piotr.golebiowski@pw.edu.pl; Tel.: +48-22-234-14-11

Abstract: The issues addressed by the article concern the assessment of energy efficiency in rail transport, resulting from the proper organization of rail traffic. The problems related to energy consumption and, thus, the negative impact of rail transport on the natural environment are highly significant in terms of the green deal concept, climate change and sustainable development. In this article, energy efficiency is investigated in the context of minimizing the energy consumption necessary to satisfy a specific transport requirement. The essence of this article is to present an approach to energy-efficient planning of rail freight traffic. This article aims to develop a method covers the allocation of railway vehicles dedicated to freight traffic (locomotives and railcars) to perform a defined transport task, taking into account the energy efficiency assessment of the solution, routing the train launched with regard to the accomplishment of the defined transport task on the railway network, and determining the conditions of transport for a defined transport task, taking into account the allocated rolling stock (locomotives and railcars) and the route. In this article, based on the presented state of knowledge, a decision-making model has been proposed, including the model's parameters, the values being searched for, indicators for assessing the quality of the solution, as well as the limitations and boundary conditions of the problem. The function of minimizing the energy consumption necessary to transport a shipment within the railway network (determining the energy efficiency of the proposed solution) has been proposed as the criterion. In addition, a description of the proprietary method of selecting rolling stock for accomplishing tasks, based on the assessment of the energy efficiency of the solution and a case study illustrating the operation of the method on the example of the area of Poland, has been presented.

Keywords: energy efficiency; rail transport; rail freight traffic planning; allocation of vehicles to tasks; mathematical modelling

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1. Introduction

Railway transport has always been predisposed for shipping mainly bulk cargo in national and international transport [1] between centres of the high concentration of cargo flows (e.g., mines or refineries) and of their termination (e.g., power plants or ports) over medium and long distances, as well as for passenger transport through international and regional services and, above all, in agglomeration areas [2–4]. The subject of this article concerns the planning of rail freight traffic; therefore, considerations will be conducted mainly in relation to this type of rail transport.

The cost of rail transport [5,6] and the dynamic development of other modes of transport mean that railway decision-makers responsible for rail transport take measures allowing an increase of interest in rail transport. This applies primarily to the implementation of innovative solutions that will allow railways to properly adapt to market expectations, in particular to customer expectations [7,8]. These solutions apply to the areas of railway transport infrastructure, means of transport [9] or additional infrastructure, enabling comprehensive customer service, as well as railway traffic organization.

As mentioned, the subject of this article is a part of the organization of rail freight traffic, which concerns a wide spectrum of issues. One of them is the selection of rolling stock for the performance of tasks. This process allows the selection of an appropriate series and number of railcars, as well as the selection of an appropriate series and number of locomotives in order to satisfy a specific transport need. An important aspect of this problem is to include considerations for the limitation of the rolling stock count.

The problem of selecting the rolling stock for accomplishing tasks can be considered from many points of view. One of them is to look for a solution with the highest possible energy efficiency. For the purpose of the article, energy efficiency will be understood as minimization of energy consumption [10] necessary to meet a transport need. Therefore, the assessment of energy efficiency will be made from the point of view of obtaining energy savings—fuel savings (electricity or diesel oil). In the case of electric locomotives, we will seek to select such a traction vehicle for which the amount of energy necessary to accomplish a given transport task will be as small as possible. As long as the weight of the cargo remains the same, the series and numbers of railcars can be selected in such a way that the total weight of the train is as low as possible. It is also necessary to select a locomotive that will require as little energy as possible to haul the cargo weight. In turn, minimization of energy consumption will contribute to the reduction of environmental pollution at the location where electricity is generated. In the case of diesel locomotives, energy is generated by combusting fuel, which causes environmental pollution at the place of energy conversion. Appropriate selection of rolling stock for the tasks will, therefore, reduce environmental pollution and, thus, contribute to implementing the concept of sustainable development [11].

Bearing in mind the above, the authors started work on selecting the rolling stock for the accomplishment of tasks, based on the assessment of its energy efficiency. Therefore, the purpose of this article is to develop a method of selecting rolling stock for the accomplishment of tasks in freight transport, taking into account limited resources based on the index of the solution quality assessment in the form of energy efficiency. This method consists of three elements. On the one hand, rolling stock is selected in the form of railway vehicles dedicated for freight traffic: locomotives and railcars for implementing a defined transport task, taking into account the fact that the rolling stock inventory is limited; on the other hand, routing is performed for the train launched in connection with executing the defined transport task in the railway network. The shipping conditions for the defined transport task are established on the basis of the obtained results.

The structure of the article has been divided into four parts. The first part includes a critical analysis of literature in the areas of: assessment of energy efficiency, rail freight traffic planning and the selection of rolling stock for rail transport tasks. The second part presents the proprietary mathematical model of selecting rolling stock for the implementation of tasks. One of the elements of this model is the index of the solution quality assessment in the form of the energy efficiency of a given solution. Parameters of the model, decision variables, objective functions as well as the limitations and boundary conditions of the problem were indicated. The third part describes the author's method of planning the rail freight traffic with limited resources, taking into account the assessment of the energy efficiency of the solution. The method is presented in both descriptive and graphic forms. The fourth part comprises the verification of the method on the basis of real data on the example of the Polish railway network.

2. Literature Review

The issue of assessing the energy efficiency in the transport sector is described quite extensively in literature. The publications can be grouped into several research areas:

- assessment of the energy efficiency of a specific mode of transport in a particular area—e.g., the European road freight [12], a specific city [13], a specific country [14],
- development of the methods for assessing the efficiency in the transport sector, based among others on such data analysis methods as DEA [15,16] and TOPSIS [17],

- review of various methods of effectiveness assessment, incl. the WTW technology [18],
- evaluation of the energy efficiency related to the processing of a particular fuel type, e.g., biochar [19], biogas [20], electricity [21], coal [22].

With regard to rail transport, research has been conducted in the scope of energy storage in light rail vehicles [23,24]. The energy efficiency of railway traffic has been studied as well [25]. The works concerning the organization of railway traffic, taking into account the energy aspect, are also worth mentioning. In the literature on the subject, one can find references to approaching this topic in various fields. The authors [26,27] dealt with the timetable optimization (starting and braking moments) in terms of energy recuperation. The work concerned the timetable of passenger trains possessing similar traction characteristics. Another group of problems refers to energy optimization during braking [28,29]. Energy audits related to train runs [30] and audits of traction substations [31] are also carried out. There occur investigations of the energy balance for different modes of transport moving through urban networks [32] and the overall efficiency of rail transport [24], as well as specific locomotive models [33].

An important area of consideration for rail transportation is the production and storage of energy in electric and diesel traction vehicles [34]. The amount of the energy produced can be estimated using analytical formulas [2,5]. The methods of improving the functioning of the railway transport system from the perspective of energy efficiency have also been reviewed [35,36].

The selection of rolling stock for the implementation of tasks is one of the elements of planning the railway transport system [36–40]. As already mentioned in the previous point of the article, it is required that a timetable be ordered from the infrastructure manager in order to be able to physically move cargo via rail transport within the railway network [41]. A few necessary parameters need to be specified while placing an order. The basic scope of input data includes the specification of the approximate route of the cargo (e.g., the shortest one), the start or end time of transportation, the locomotive series and the weight of the train. On this basis, a timetable will be prepared, and the costs of passage will be determined [42]. Obtaining the aforementioned parameters is possible using the method which is the subject of this paper.

The planning of rail transport services may be considered in terms of the length of the planning horizon and the variety of decision issues. The following planning horizons can be distinguished: strategic, tactical, operational and real-time planning (Figure 1).

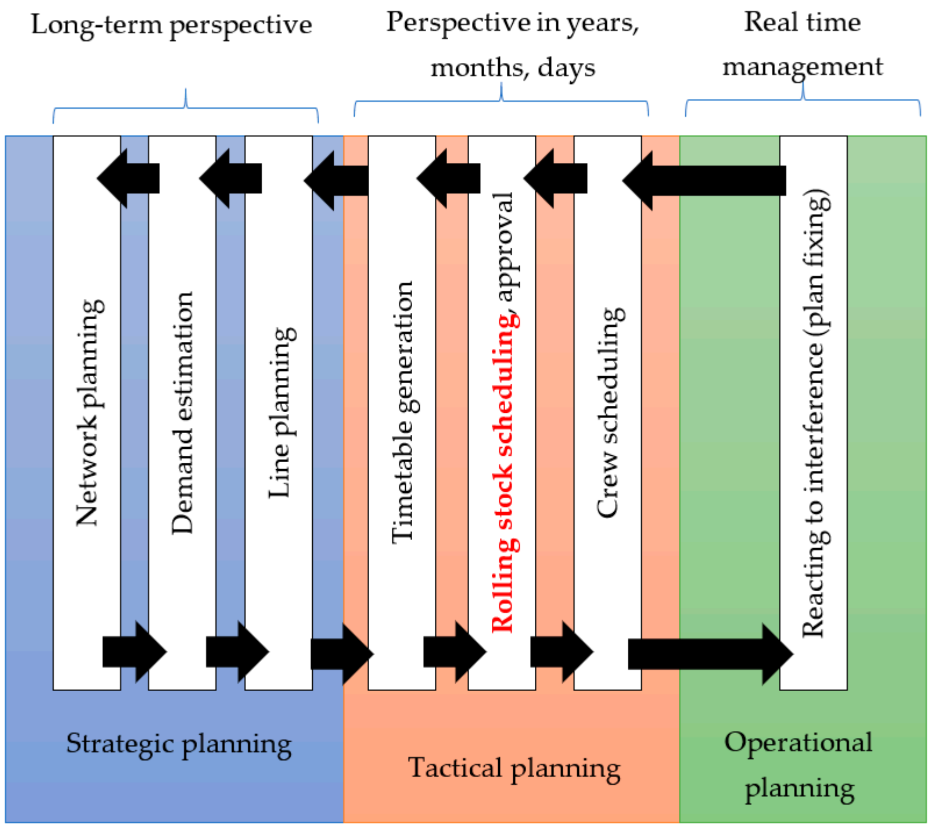

Figure 1. Individual steps of planning the rail transport system. Source: the authors' own elaboration based on [43,44].

The focus of interest for this article is the allocation of rolling stock for the implementation of tasks based on the assessment of energy efficiency of the obtained solutions. As can be seen in Figure 1, this problem falls within the realm of tactical planning, i.e., in the time perspective expressed in years, months or days. The selection of rolling stock for tasks ought to indicate how many locomotives and of which series, and how many freight cars of specific series are needed to perform the tasks and how to combine them to meet the transport requirements resulting from the recipients' demand. This issue varies depending on the cargo and takes different forms. Primarily, it takes into account other assumptions and limitations, e.g., transportation of passengers or cargo. The three main criteria for planning rolling stock are quality of service, operational costs and resistance to interference [45].

The selection of rolling stock (locomotives and railcars) for the implementation of freight tasks in rail freight transport is one of the elements of the Task Allocation Problem (TAP) [46]. This problem is derived from computer science, where the definition includes [46] processors, tasks, transitions between the tasks and costs. Referring to the field of rail transport, the rolling stock will be the processor, the tasks will consist in transportation and additionally we will have specific connections between tasks. All costs should be defined. In the literature, one can find many formulations of this problem [47–49] and many methods of solving it [50,51].

Several mathematical models have been developed for freight traffic planning [52]. In the literature, you can find papers in which a similar method of mapping the railway network was used as in this article, using graph theory [53]. Noteworthy is the use of operational research methods to freight traffic planning [54,55]. Researchers also analyzed many optimization problems [56].

The operation of the rolling stock is an important cost component in rail transport —certainly from the point of view of the rail carrier. Its purchase alone is associated with large investments. In addition, the costs of its servicing should be added. For this reason, it is extremely important to properly plan the required size of rolling stock inventory in the strategic plan. In the implementation of the operational plan, the ideal situation is the lack of empty runs. However, it is quite difficult to implement. It is related not only to the costs of the carriage itself, but also to the costs of purchasing and maintaining a large number of means of transport, as well as losses from track occupancy and additional shunting operations as well as employing the crews [45]. While planning the selection of rolling stock for tasks with limited resources, a situation may arise when in a certain period of time more trains depart from one station than return to it. Such a situation is called imbalance and causes the necessity of operating empty runs. On this account, the effective management of the rolling stock is very important for the effectiveness of the railway system operation. The life cycle of rolling stock usually lasts several decades, so investments cannot be implemented and changed frequently. Therefore, it is necessary to precisely plan the demand and adjust the appropriate size of rolling stock inventory in comparison against the level of demand for transport.

A properly implemented process of planning the selection of railway vehicles for tasks includes considerations for both external factors [57] and limitations. Due to the scale of the actual problems [58,59] concerning the planning of rolling stock selection (resulting, among others, from the diversity of rolling stock and legal conditions), a very large number of decision variables and restrictions should be taken into account in the mathematical model. Taking into account some constraints in the model increases the level of complexity of the problem and the number of calculations necessary to generate the optimal set of trains to be served by a given train composition.

3. Methodology

3.1. Mathematical Model of the Problem

As already mentioned, the main area of interest in this article is rail freight traffic, in particular the problem of selecting rolling stock (railcars and locomotives) for the implementation of freight transport within the railway network. This selection is based on the assessment of the energy efficiency of the solution obtained. It should be noted that an appropriate selection of the rolling stock is not possible without knowing the parameters of the railway line along which this transport will be carried out. Therefore, for the purposes of completing this article, the selection of rolling stock for the implementation of tasks is understood as:

- allocation of railway vehicles dedicated to freight traffic: locomotives and railcars to perform a defined transport task, taking into account the fact that the size of rolling stock inventory is limited; the solution is assessed in terms of the energy efficiency of the allocation,
- routing of a train launched in connection with the implementation of a defined transport task within the railway network,
- determination of transport conditions for a defined transport task taking into account the allocated rolling stock (locomotives and railcars) and the route.
- In order to select the rolling stock to perform specific tasks, it is necessary to:
- identify the location of the shipping points and unloading points as well as intermediate operating points for the implementation of transport—***GSK***,
- determination of technical characteristics of point elements (forwarding points) and linear railway network, e.g., unloading and loading times or travel times along a given route section—***FSK***,
- determination of locomotives and railcars being at the disposal of the railway operator—***ST***, i.e., determination of the technical characteristics of a given locomotive or railcars, e.g., max. speed, number of axles, capacities etc.—***FST***,
- defining the size of tasks to be performed (the size of the transported freight in a given service)—***ZPD***,
- defining transport tariffs—***TTP***,
- determining the energy efficiency of a specific transport task performance—***EE***.

Thus, the ***MDTEE*** model can be represented using an ordered seven:

$$\boldsymbol{MDTEE} = \langle \boldsymbol{GSK}, \boldsymbol{FSK}, \boldsymbol{ZPD}, \boldsymbol{ST}, \boldsymbol{FST}, \boldsymbol{TTP}, \boldsymbol{EE} \rangle \tag{1}$$

The main assumptions of the rolling stock selection model to meet the transport needs are as follows:

- the performance of the transport task consists of transporting a specific volume of cargo from senders to recipients,
- cargo is transported with the use of locomotives and railcars suitable for the cargo being transported according to the NHM catalogue [60],
- the performance of transport tasks takes place within the established rail transport network,
- in the case of launching a train with a loading gauge exceeded, lines adapted to this will be used,
- the route of the shipment (transport task), constituting a transport need, should consist of successive sections of the railway line,
- the performance of a given transport task is carried out according to the appropriate transport tariff (basic charge appropriate for a given transport task changed with the use of an appropriate combination of multipliers),
- optimization takes place at the level of a specific transport task, and not at the network level,
- we assume that the capacity is available for the implementation of the reported transport task; the possible lack of capacity on individual open line may result in the extension of the obtained transport time,
- we assume that the current state of the rolling stock at the disposal is the input data; we determine the best solution for this state; we do not assume its update and implementation delay (one of the criteria is minimizing the duration of the transport),
- we assume that the task is performed with the use of the block train system; in the future, we will extend the method to the implementation of transport in the single wagon system.

The model and the method can be applied to any area of the railway network. It all depends on what network input data will be entered into the program. The experiments with the model and method were conducted for the territory of Poland, and more specifically for the railway infrastructure managed by PKP Polskie Linie Kolejowe S.A. As already mentioned, service areas in the rail freight transport are especialy block train system. The rolling stock that can be used to perform a transport task is also an input data to the model. Usually, data related to a specific railway undertaking are entered. The experiments used the data of the largest freight carrier in Poland—PKP Cargo S.A.

3.2. Mathematical Formulation of the Problem

3.2.1. Model Parameters

The problem of selecting the rolling stock for the implementation of tasks based on the assessment of the energy efficiency for a given solution consists in determining the following values of the decision model:

- binary variables $x(nol,zpd)$ about the interpretation of the use of a given section of the railway network for the implementation of a specific transport task, stored in the matrix $\mathbf{D}(zpd)$,
- binary variables $dtr(zpd,lok,wag)$ about the interpretation of allocating an appropriate number of locomotives of specific series and a specified number of railcars of specific series for the implementation of a given transport task, stored in the matrix $\mathbf{DTR}(zpd)$,
- variables about the interpretation of the conditions of transporting the shipment being declared for transport for a specified route and selected locomotive and railcars, notated in the form of a vector $\mathbf{WP}(zpd)$:

$$\mathbf{WP}(zpd) = \begin{bmatrix} sp(zpd, pe), sk(zpd, pe), dl(zpd), \mathbf{O}(zpd), \\ \mathbf{VMAX}(zpd), \mathbf{NMAX}(zpd), \mathbf{WMAX}(zpd), \\ \mathbf{OMAX}(zpd), \mathbf{DMAX}(zpd), rzmh(\mathbf{DTR}(zpd)), \\ \mathbf{TNOL}(zpd), t(zpd), k(zpd) \end{bmatrix} \tag{2}$$

where:

- *dl*(*zpd*)—length of the transport task route,
- **O**(*zpd*)—a vector containing a list of railway line sections along which the transport needs will be fulfilled,
- **VMAX**(*zpd*)—a vector containing a list of permissible speeds for sections of railway lines along which the transport needs will be fulfilled,
- **NMAX**(*zpd*)—a vector containing a list of permissible axle loads for sections of railway lines along which the transport needs will be fulfilled,
- **WMAX**(*zpd*)—a vector containing a list of the permissible number of railcars for sections of railway lines along which the transport needs will be fulfilled,
- **OMAX**(*zpd*)—a vector containing a list of the permissible number of axles for sections of railway lines along which the transport needs will be fulfilled,
- **DMAX**(*zpd*)—a vector containing a list of the permissible length of trains for sections of railway lines along which the transport needs will be fulfilled,
- *rzmh*(**DTR**(*zpd*))—total braked weight of the train: of the dispatched locomotive and dispatched railcars,
- **TNOL**(*zpd*)—a vector containing theoretical travel times for sections of railway lines along which the transport needs will be fulfilled,
- *t*(*zpd*)—theoretical travel time for the fulfilment of the transport need,
- *k*(*zpd*)—transport cost for the fulfilment of the transport need.

In order to solve the problem, it was necessary to define the characteristic parameters concerning the transport task, infrastructure, rolling stock, freight tariff and energy used for transport performance. The model parameterization should begin with defining the transport task. Each transport task *zpd* defined by the commodity group *nhm* possesses specific characteristics. They were notated with the following parameters:

- *tow*(*zpd*,*nhm*)—the subject of carriage in the transport task is the commodity with the number NHM,
- *sp*(*zpd*,*pe*)—the transport task with the *zpd* number begins at the operating point *pe* called the point of dispatch,
- *sk*(*zpd*,*pe*)—the transport task ends at the operating point *pe* called the collection point,
- *zp*(*zpd*)—the size of the transport need,
- *ps*(*zpd*)—the fact that the transport need is a shipment with the loading gauge exceeded.

It is assumed that each transport task will be described by the vector **ZPD** of parameters, i.e.,

$$\mathbf{ZPD} = [zpd, tow(zpd, nhm), sp(zpd, pe), sk(zpd, pe), zd(zpd), ps(zpd)] \tag{3}$$

Another element of the model is the railway network along which the analyzed transport task will be performed. The railway network consists of point and line elements of the railway transport infrastructure. For the purposes of this article, it is assumed that point elements of the railway infrastructure will be represented by operating points (signal boxes (i.e., stations and junction signal boxes) and passenger and cargo handling points) and will be marked with the symbol *pe*. Operating points are connected with each other by sections of railway lines marked with the symbol *nol*.

Pe operating points are characterized by the following parameters: the maximum number of railcars that can move at the site of the point—*ows*(*pe*), the maximum number of railcar axles that can enter the point—*oos*(*pe*), the maximum number of train axles that can enter the area of the point—*oops*(*pe*), the maximum length of the train that can enter the area of the point—*odps*(*pe*). Thus, it is assumed that each passenger and cargo handling point will be described by the vector of parameters **FPE**, i.e.,:

$$\mathbf{FPE} = [ows(pe), oos(pe), oops(pe), odps(pe)] \tag{4}$$

On the other hand, the sections of railway lines *nol* are characterized by the following parameters: length—*okm*(*nol*), maximum permissible speed—*ov*(*nol*), maximum permissible axle load—*og*(*nol*), the possibility of passage for trains with the loading gauge exceeded—*op*(*nol*), the maximum number of railcars that can run along a section—*owo*(*nol*), the maximum number of axles that can enter the section—*ooo*(*nol*), the maximum length of a train that can enter the section—*odpo*(*nol*), type of traction—*ot*(*nol*), required percentage of braked weight—*pmh*(*nol*). Therefore, it is assumed that each section of the railway line will be described by the vector **FOL** with the following parameters, i.e.,:

$$\mathbf{FOL} = \begin{bmatrix} okm(nol), ov(nol), og(nol), op(nol) \\ owo(nol), ooo(nol), odpo(nol), ot(nol), pmh(nol) \end{bmatrix} \tag{5}$$

The basic element while analyzing the method of carrying out transport tasks is the identification of the dedicated rolling stock along with its characteristics. From the point of view of this article, two types of rolling stock will be important: locomotives and freight cars. Locomotives *Lok* are characterized by the following parameters: series—*ls*(*lok*), towing capacity—*lm*(*lok*), number of axles—*lo*(*lok*), length—*ld*(*lok*), empty weight—*lc*(*lok*), maximum speed—*lv*(*lok*), type of traction—*lt*(*lok*), number—*ll*(*lok*), percentage of braked weight—*hl*(*lok*). Thus, it is assumed that each locomotive will be described by the vector **FL** of the following parameters, i.e.,:

$$\mathbf{FL} = \begin{bmatrix} ls(lok), lm(lok), lo(lok), ld(lok), \\ lc(lok), lv(lok), lt(lok), ll(lok), hl(lok) \end{bmatrix} \tag{6}$$

In turn, railcars *wag* are characterized by the following parameters: series—*ws*(*wag*), number of axles –*wo*(*wag*), length—*wd*(*wag*), empty weight—*wc*(*wag*), load capacity—*wl*(*wag*), maximum speed—*wv*(*wag*), percentage of braked weight—*hw*(*wag*), assigning a railcar of a specific series *ws*(*wag*) to particular types of goods codified under NHM—*wnhm*(*ws*(*wag*),*nhm*). Thus, it is assumed that each railcar will be described by the vector **FW** having the following parameters, i.e.,:

$$\mathbf{FW} = \begin{bmatrix} ws(wag), wo(wag), wd(wag), wc(wag), \\ wl(wag), wv(wag), wnhm(ws(wag), nhm) \end{bmatrix} \tag{7}$$

To determine the value of the transport charge for its performance, it is necessary to determine the value of the following parameters: the amount of the basic charge for the transport task for the section—*op*(*zpd*,*nol*), the amount of the correction coefficient for the transport task—*wsk*(*zpd*), the amount of the additional charge for the transport task—*od*(*zpd*). Therefore, it is assumed that each transport task will be described by the vector **TTP** of the following parameters, i.e.,:

$$\mathbf{TTP} = [op(zpd, nol), wsk(zpd), od(zpd)] \tag{8}$$

The last group of the parameters which are necessary to correctly solve the problem of selecting the rolling stock for the fulfilment of tasks with limited resources is the determination of the amount of energy *en*(*nol*,*zpd*,*lok*,*wag*) necessary to run a train along a specific section in order to fulfil a specific transport need with the use of a certain number of locomotives of specific series and a certain number of railcars of particular series. This parameter will be the basis for determining the energy efficiency of the proposed solution based on the dependencies contained in [2].

3.2.2. Quality Assessment Indices for Solving the Problem of Selecting the Rolling Stock for the Implementation of Tasks Based on the Assessment of the Energy Efficiency of the Solution

Heuristic algorithms were used to solve the problem of selecting the rolling stock for the performance of tasks on the basis of energy efficiency assessment. These algorithms usually generate solutions in a random way. Then, the value of the objective function, i.e., the index of solution quality assessment, is calculated, and the best value, basing on a defined extreme, is selected. The values of the decision variables are read for this value and thus a final solution is obtained. The following criteria were adopted to assess the quality of the solution to the analyzed problem:

- $F_1(k(zpd))$—minimizing the cost of shipment transport within the railway network:

$$F_1(k(zpd)) = \sum_{nol \in NOL} k(zpd) \cdot x(nol, zpd) \rightarrow \min \tag{9}$$

- $F_2(\mathbf{D}(zpd), \mathbf{DTR}(zpd))$—minimizing energy consumption necessary to carry out the shipment transport within the railway network (determination of the energy efficiency of the proposed solution):

$$F_2(\mathbf{D}(zpd), \mathbf{DTR}(zpd)) = \sum_{nol \in NOL} \begin{array}{c} dtr(zpd, lok, wag) \cdot x(nol, zpd) \cdot \\ \cdot en(nol, zpd, lok, wag) \end{array} \rightarrow \min \tag{10}$$

From the point of view of this article index 2 is the most important one. The amount of energy is determined separately for each section of the railway line on the basis of allocated locomotives and railcars for the implementation of a specific task.

3.2.3. Constraints Used in the Problem of Selecting the Rolling Stock for the Performance of Tasks Based on the Assessment of the Energy Efficiency of the Solution

Solving a decision problem requires defining many constraints and boundary conditions in the scope of:

- train parameters concerning:
    - maximum train speed,
    - maximum axle loads of vehicles (locomotives and railcars),
    - actual braked weight of the train composition,
    - necessity to meet a transport need with the loading gauge exceeded,
- shipment parameters concerning:
    - a specific load should be transported in a railcar of a specific series in agreement with its allocation,
    - the place of transport commencement,
    - the place of transport completion,
    - allocating an appropriate number of railcars,
    - allocating a locomotive whose towing capacity will allow the train to move,
- infrastructure parameters concerning:
    - transport route,
    - a given section of the railway line,
    - the number of railcars allocated for task performance,
    - number of railcar axles allocated for task performance,
    - the sum of the length of the locomotive and railcars allocated for task performance,
    - the sum of the number of locomotive and railcar axles allocated for task performance,
    - allocation of a locomotive whose type of traction corresponds to the type of traction located on individual sections of railway lines,
    - bearing a basic charge and possibly an additional fee,

- imposing correction factors.

3.3. The Procedure of the Method

In point 3.2 of this article, the decision model of the research problem was presented, which was the selection of rolling stock for task performance based on the assessment of the energy efficiency of the solution. The main task of this method is to obtain a solution to the formulated decision-making model. Obtaining specific numerical values of the defined decision variables for which the stored criterion functions reach extreme values will be the solution to the task. The solution should meet the imposed boundary conditions of the task (constraints). The scheme of the method is presented in Figure 2.

The method of selecting the rolling stock for performing tasks in rail transport based on the assessment of the energy efficiency of the solution can be notated as follows.

- **STEP 1**: Defining the input parameters. It is necessary to define the initial and terminal stations for commodity transport, define their type and the amount of weight to be transported.
- **STEP 2**: Using the input parameters and the "Stations" dictionary (STEP 2a) it is possible to describe the transport task (STEP 2b). When describing the task, the "NHM" dictionary containing standardized types of cargo should be used, so that the type of commodity is written in the form of commodity groups to be transported (STEP 2c).
- **STEP 3**: Identifying the data being searched for: incl. locomotives, railcars, train length, number of axles, weight, speed, percentage of braked weight.
- **STEP 4**: Answering the question whether the first search for a solution is taking place. If **not**, go to the "Restrictions and conditions of train passage" section. If **yes**, go to the next step.
- **STEP 5**: On the basis of the dictionary "Locomotives" and "Railcars", the allocation of vehicles for the performance of the defined transport task takes place.
- **STEP 6**: Define the train composition necessary for the transport by determining its weight, length, number of railcars, number of axles, maximum axle load on the rail and maximum speed.
- **STEP 7**: Basing on the specified parameters of the train composition, as well as on the basis of the data contained in the dictionaries "Stations", "Railway lines" and "Railway sections", the optimal route for the transport is determined by specifying: maximum speed, maximum axle load on the rail, type of traction and loading gauge parameters.
- **STEP 8**: As a result of the work, we obtain a set of restrictions and conditions for train passage. The limitations arise by comparing the values found with the parameters of the train route (STEP 8a). In the scope of transport conditions, the tariff cost, is determined, i.e., pursuant to the "Freight Tariff" dictionary.
- **STEP 9**: A report on results is generated, in the form of determining the train composition, restrictions and running costs.
- **STEP 10**: Verifying the correctness of the obtained results. If the results are correct, the operation of the method ends. If the obtained results are not satisfactory, the assumptions are changed (STEP 10a). Corrections may be introduced by changing the locomotive, changing the train composition or changing the route (STEPS 10b, 10c and 10d). After a correction is made, go to step 8 "Train passage restrictions and conditions".

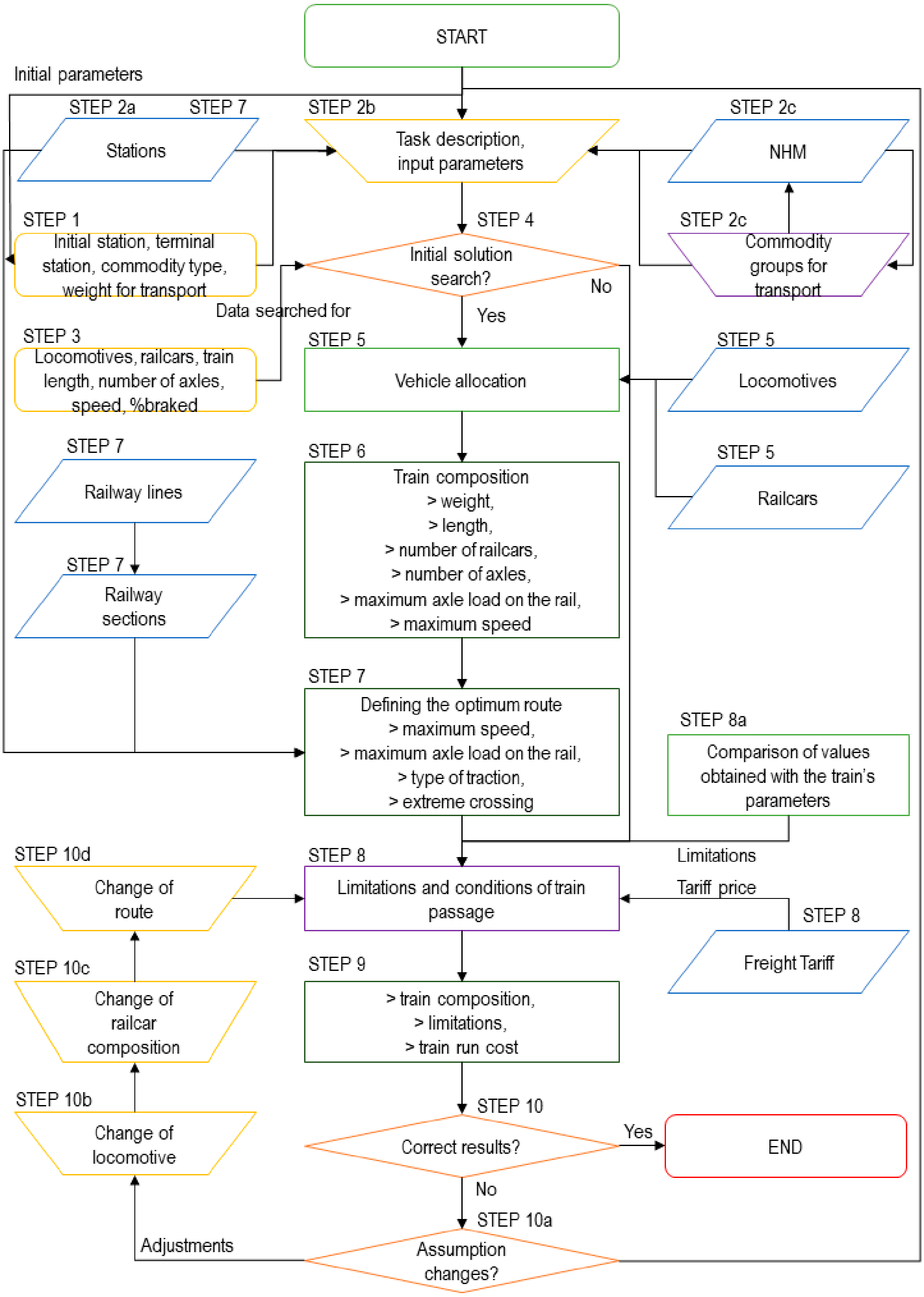

Figure 2. The block diagram of the method of planning rail freight traffic with limited resources. Source: the authors' own elaboration.

4. Case Study—Selection of Rolling Stock for Task Performance on the Basis of the Assessment of Energy Efficiency of the Solution on the Example of Poland

4.1. Identification of Input Parameters

Verification of the correctness of the method of selecting rolling stock for the purpose of task performance in rail transport on the basis of energy efficiency assessment was carried out for a selected area of the railway network. This area is the railway network of the largest Polish railway infrastructure operator: PKP Polskie Linie Kolejowe S.A. This operator is responsible for the maintenance of 18,679.9 km of active railway lines (of which 99.2% are standard-gauge lines, and 0.8% are broad-gauge lines), which accounts for 95.8% of the total length of operated railway lines in Poland. There are approximately 2200 signal boxes and operating points within the network of PKP PLK, which are important from the point of view of freight traffic. Relevant points are connected (linked) with each other by sections of railway lines. The railway network of Poland (with a detailed specification of the research area as an example) with marked operating points is shown in Figure 3.

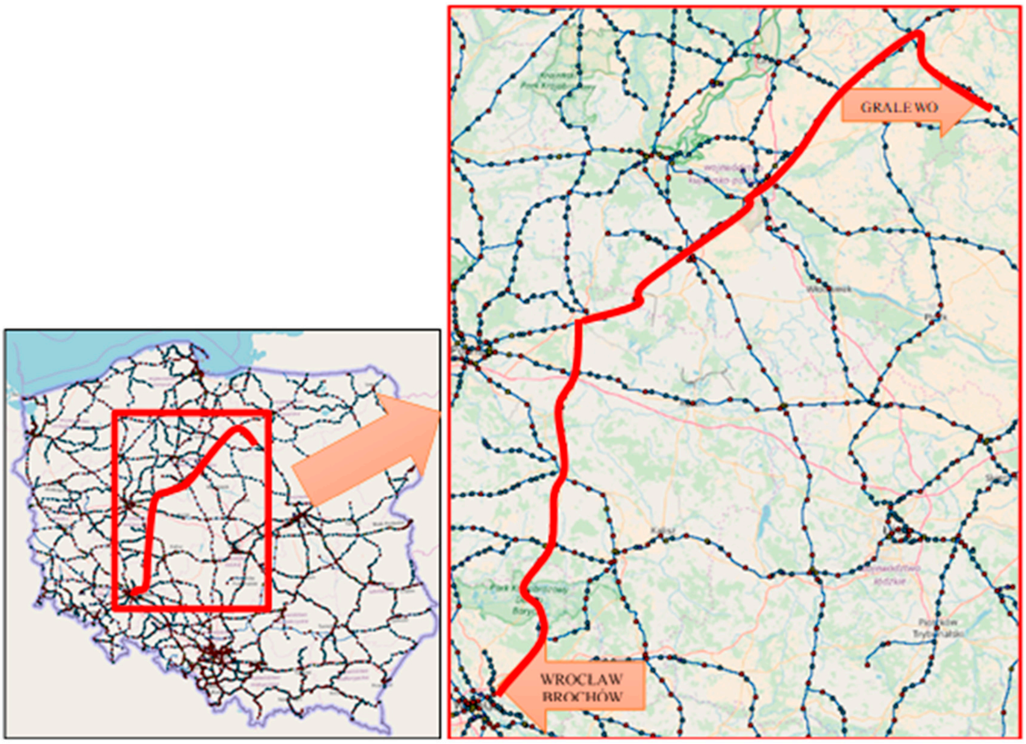

Figure 3. Polish railway network (with a detailed specification of the research area as an example). Source: http://mapa.plk-sa.pl/ (accessed on 7 June 2021).

The work on the verification of the method should begin with defining and parameterizing the railway network along which the cargo declared for transport will be moved. The next stage of the work is to define the parameters of the rolling stock, which is at the disposal of the railway carrier selected for transport and which is connected with fulfilment of the transport needs. The method was examined using the data on the largest freight carrier in Poland—PKP Cargo S.A. This carrier owns around 2 thousand locomotives and 60 thousand railcars. For the correct verification of the method, individual series of locomotives and their technical parameters were defined (based on [61,62]), as well as individual series of freight cars and their technical parameters (based on [63]). The limitation of resources was estimated on the basis of data available, i.e., in [61–63]. In addition, a railway network was defined—the research was carried out for the territory of Poland.

In order to determine the specific conditions of transport, it is necessary to specify the data concerning the freight tariff. For the purposes of this research, it was assumed that the freight tariff of PKP Cargo would be used [64]. It includes all the values of basic charges, multipliers and adjustment factors.

Planning rail freight traffic with limited resources may only take place after defining the transport task which is to be performed and its appropriate parameterization. It is therefore necessary to define:

- the object of transport: stones for the construction of a railway line,

- the initial station of transport: Gralewo,
- the terminal station of transport: Wrocław Brochów,
- the weight of the object of transport: 2000 tons,
- information that the shipment is not a shipment exceeding the loading gauge.

4.2. Results of the Selection of Rolling Stock for the Implementation of Tasks Based on the Assessment of Energy Efficiency of the Solution

The result of the conducted simulations of the selection of rolling stock for the implementation of tasks based on the assessment of energy efficiency of the solution is:

- carrying out an allocation of railway vehicles dedicated to freight traffic: an appropriate number of the correct series of locomotives and an appropriate number of the correct series of freight cars to perform the defined transport task,
- routing a train launched in connection with the implementation of a defined transport task within the railway network (taking into account the effects of the selecting rolling stock for task performance,
- identifying transport conditions for a specified transport task.

4.2.1. Selecting a Locomotive and Railcars to Perform the Transport Task

As already mentioned, the subject of the case study is the selection of rolling stock for the transport task, which is the transport of stone from the Gralewo station to the Wrocław Brochów station. As a result of the conducted simulations, the following form of results concerning the selection of rolling stock for the analyzed task was obtained. The results are presented in Table 1.

Table 1. Results of the selection of rolling stock for the performance of the task 0100.

Vehicle	Parameter	Parameter Value
LOCOMOTIVES	series	**ET21** (electric)
	number	1
	axles in total	6
	total length	17.5 m
	max. speed	100 km/h
	empty weight	78 tons
	braked weight	50 tons
	percentage of braked weight	64.1%
	max. axle load of the locomotive on the rail	13 tons
RAILCARS	series	**Eans**
	number	19
	number of railcars	19
	axles in total	76
	total length	342 m
	max. speed	100 km/h
	empty weight	427.5 tons
	braked weight	950 tons
	percentage of braked weight	62.5%
	load limit	1520 tons
	max. axle load of the railcar on the rail	20 tons

Source: the authors' own elaboration.

The conducted simulation showed that the transport of stone from the Gralewo station to the Wrocław Brochów station should be carried out with the use of one electric locomotive adapted to freight traffic of the **ET21** series and **19 freight cars** of normal construction of the **Eans** series. The number of calculation axles of the train is **82**, and its length is **359.5 m**. The braked weight of the train is **1000 tons**, and the percentage of the braked weight is **62.6%.**

4.2.2. Determining the Route of Freight Transport

The second element of the problem of selecting rolling stock for the performance of tasks on the basis of energy efficiency assessment is the determination of the proposed (shortest) route of train passage. As a result of the simulation, a route proposal was obtained, which is illustrated in Figure 4.

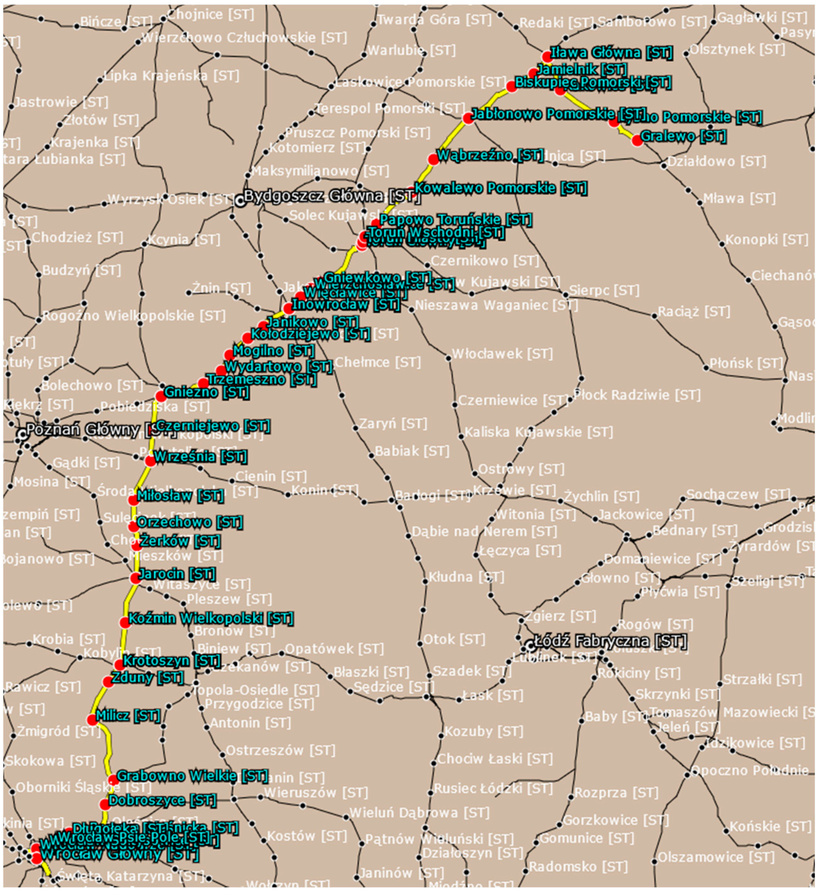

Figure 4. The course of the route for the selected transport task. Source: depiction of simulation results with the use of the website https://skrj.plk-sa.pl/kalkulacja/ (accessed on 7 June 2021).

4.2.3. Determining the Conditions of Transport for Individual Tasks

A transport route was defined for the analyzed transport task. The route runs through Iława, Toruń, Inowrocław, Gniezno, Września, Jarocin, Krotoszyn and Oleśnica. It is **428,076 km** long. Designating the route facilitated determination of the maximum speed for the train at the level of **80 km/h**. Given this data, it was possible to determine the approximate lead time which at the level of = **317.25 min**. When determining this value, it was assumed that the duration of the electric locomotive reception is **15 min**, and the duration of departure is **15 min**. In addition, the cost of freight transportation was established, and it amounts to **PLN 213 894.40**. This cost includes the tariff price at the level of **PLN 3 518.00.** multiplied by a correction factor of **60.8**. The total amount of energy emitted during the passage is **9.61 MWh**, which can be converted into the emissions of harmful compounds amounting to: **6.67 Mg CO_2**, **0.019 Mg SO_2**, **0.015 Mg NO_x**, **0.00048 Mg PM**.

The solution proposed is characterised by the highest energy efficiency. This means that the selected locomotive and railcars allow for implementing the transport task with the achievement of highest energy savings. The proposed route is adapted to the selected vehicles. It should be noted that improvements in energy efficiency for the proposed solution may be achieved through properly designed train timetable (please note, that we assume that the capacity is available for the implementation of the reported transport task; the possible lack of capacity on individual open line may result in the extension of the obtained transport time). Such timetable should be characterised by a minimum number of stops or speed reductions and increases.

5. Summary and Conclusions

The article presents a method of selecting railway rolling stock for task performance in freight transport, which takes into account the limited resources, based on the index of the solution quality assessment in the form of energy efficiency. This indicator describes the minimization of energy consumption necessary to execute the transport of a shipment within a railway network (determination of the energy efficiency for the suggested solution). The magnitude of energy consumption is primarily influenced by the size of the transport need. Proper selection of the traction vehicle and railcars may increase or reduce this consumption. It is therefore prudent to search for methods that will make the obtained solution dependent on the amount of energy used for the performance of a specific transport task.

The method consists of three elements. On the one hand, rolling stock is selected in the form of railway vehicles dedicated for freight traffic: locomotives and railcars for implementing a defined transport task, taking into account the fact that the rolling stock inventory is limited; on the other hand, routing is performed for the train launched in connection with executing the defined transport task in the railway network. On the grounds of the obtained results, the transport conditions for the defined transport task are established. Owing to this assumption, on the basis of the selected rolling stock, a route suitable for it is selected and the conditions of transport are determined. One of the method's limitations is that only three NHM commodity groups are assigned to a specific wagon. If a given type of freight has not been assigned to a particular type of wagon and can be transported in it, we can obtain a solution that will not be the best. This can only be corrected manually by the operator. Another limitation is that the method constantly searches for the shortest route of cargo transportation. Sometimes it may not be the best. This can only be corrected manually by the operator.

In order to solve the problem, a heuristic algorithm was proposed, which allows for selecting the best solution from the set of admissible solutions, using the multi-criteria optimization method. Appropriate weights were assigned to each of the aforementioned criterion functions. The highest importance was assigned to the function describing the energy expenditure related to transportation fulfilling a specific transport need. Owing to this, the obtained solution is the most favourable from the point of view of energy efficiency. The use of the heuristic algorithm resulted in one of the method's limitations—the obtained solution may not be optimal but suboptimal. Therefore, we are not sure if the obtained solution is the best one.

The outcome of this article is addressed to representatives of railway carriers. Thanks to the developed method, these institutions will be able to rationally manage their rolling stock. The application, which was developed for the purposes of this work, enables manual correction of the solutions suggested automatically, which allows better adaptation of the obtained solution to customer needs in line with the cargo carried and customers' expectations.

In terms of the directions of further research, it should be mentioned that the possibility of adapting the method to the current needs, taking into account the latest available algorithms and their modifications. The authors mean changes in both the mathematical model, the procedure of the method and the computer application. In addition, the following research areas should be mentioned among the directions of further research:

- planning train traffic on the railway network in a variant other than the shortest,
- planning train traffic on the railway network in the form of graphic timetable,
- planning the work of traction crews in terms of assigning a traction crew to service trains,
- planning of maneuvering work and the operation of the support facilities in setting maneuvering crews to individual stations with shunting locomotives and drawing up a plan for the maintenance of traction vehicles and wagons by technical facilities (inspections).

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