Scientific Journal of Silesian University of Technology. Series Transport
Zeszyty Naukowe Politechniki Śląskiej. Seria Transport

Volume 120 **2023**

p-ISSN: 0209-3324

e-ISSN: 2450-1549

DOI: https://doi.org/10.20858/sjsutst.2023.120.16

Journal homepage: http://sjsutst.polsl.pl

Article citation information:
Szczepański, E., Gołębiowski, P., Kondracka, B. Evaluation of the technological process of wagon processing at shunting stations using the simulation model. *Scientific Journal of Silesian University of Technology. Series Transport*. 2023, **120**, 249-267. ISSN: 0209-3324. DOI: https://doi.org/10.20858/sjsutst.2023.120.16.

Emilian SZCZEPAŃSKI[1], Piotr GOŁĘBIOWSKI[2], Barbara KONDRACKA[3]

EVALUATION OF THE TECHNOLOGICAL PROCESS OF WAGON PROCESSING AT SHUNTING STATIONS USING THE SIMULATION MODEL

Summary. Shunting stations play an essential role in ensuring the proper functioning of the railway transport system. The proper organisation of their work allows trains to be dispatched on time and compensates for delays in other areas of the railway network. This paper presents a method for evaluating the technological process of wagon processing at shunting stations based on the author's formulation of evaluation measures and using a simulation model developed in Flexsim. A variant computational example was developed to verify it and demonstrate its capabilities. The method has many applications in assisting decision-makers in organising shunting station operations, adapting the shunting station layout to the tasks or identifying bottlenecks.

Keywords: railway transport, shunting station, wagon processing, simulation research

[1] Faculty of Transport, Warsaw University of Technology, Koszykowa 75 Street, 00-662 Warsaw, Poland. Email: emilian.szczepanski@pw.edu.pl. ORCID: https://orcid.org/0000-0003-2091-0231
[2] Faculty of Transport, Warsaw University of Technology, Koszykowa 75 Street, 00-662 Warsaw, Poland. Email: piotr.golebiowski@pw.edu.pl. ORCID: https://orcid.org/0000-0001-6885-7738
[3] Faculty of Transport, Warsaw University of Technology, Koszykowa 75 Street, 00-662 Warsaw, Poland. Email: b.kondracka@wp.pl. ORCID: https://orcid.org/0009-0003-7732-8143

1. INTRODUCTION

The passenger and freight railway market are constantly developing technologically. It is an area where new investments are planned, whether in modern technologies, control command and signalling systems or infrastructure investments to improve the quality of services. The need to develop railway transport results from the need to increase its share in transport and reduce transport by road, for example. Unfortunately, this transport branch is characterised by several limitations, including lower flexibility, so it is necessary to look for solutions to compensate for them. It can be achieved by introducing modern solutions regarding rolling stock, infrastructure or organisation of transport, supporting scientific research and innovation, and introducing new legislative regulations and preferential conditions for the railway transport system [17].

Railway transport infrastructure is divided into linear and nodal. In this system's operation, the nodal elements' functioning is crucial. The organisation of their operation affects the handling of trains. If service times at a node are extended, a train service at a station will be dispatched from that station late. It will adversely affect the process of running trains and, consequently, the timetable. At the same time, the well-organised operation of such points makes it possible to ensure the rhythmicity of traffic on the network and compensate for disturbances from other elements of the system [16, 27, 30, 40].

The main task of shunting stations is separating and grouping wagons into individual directions according to the established wagon relations, putting together and setting out of trains. The individual operations that train sets and wagons undergo are called processing. Units such as a train set, wagon set, wagon group or wagon are subject to processing. Besides organisation, the processing is influenced by the design and layout of the station, as well as the characteristics and availability of resources [22]. The matching and integration of these components significantly impacts the operation of the railway transport system, and accomplishing this task requires appropriate methods and decision-support tools. There is a lack of universal decision support methods in the literature and practical applications for evaluating station performance from a system perspective.

This article aims to present the author's approach to assessing the technological process of processing freight wagons at shunting stations. The approach considers the developed technological process evaluation measures and a simulation model made in the Flexsim environment. It allows for evaluating the realisation of wagon processing and comparing different solutions in absolute values. The proposed evaluation method is practically and scientifically applicable and fills a research gap in decision-support methods for freight wagon machining processes. It should be emphasised that it can also be applied to passenger wagons.

The remainder of the article is organised as follows. Part 2 presents an overview of the state-of-the-art and current research in the field of shunting station organisation and the use of simulation methods. Part 3 characterises the technological process of wagon processing at a shunting station. Part 4 presents the author's evaluation method using a simulation model and process evaluation measures. In part 5, a computational example using the developed method is carried out. The article concludes with a summary and directions for further research.

2. LITERATURE REVIEW

Decisions concerning station operations' organisation include receiving a trainset, marshalling, accumulating groups of wagons, and forming a new trainset. In addition, the literature addresses the problem of scheduling the formation and departure of trains. However, in planning at the operational level, the most extensively described decision problem is dividing a trainset into wagon groups and sorting them through the marshalling yard or the extraction tracks to the directional tracks. In [41], the authors address the Train Formation Problem (TFP), in which trainsets are formed considering the transport demand over a certain period and the profiles of consignments, traction and according to the specific purpose and physical and operational constraints of the railway network. Therefore, the solution to this problem is related to the operation of the nodal railway station at the tactical planning level. Determining the appropriate configuration of trainsets impacts the station operation's efficiency and the marshalling process's organisation. In [41], the authors propose a method for optimising train formation by considering integer mathematical programming. The problem is solved without considering the specifics of individual stations, but from the point of view of the railway network and considers shunting stations only as vertices in a graph with a specific capacity.

From the point of view of the operation of nodal railway stations, decisions concerning the timetable of trains, the directions served by a station, and train marshalling strategies are significant. These strategies may concern the order in which trains are operated, the priority of service for particular trains or wagons, and other additional activities carried out on the trainset (e.g. loading operations, service operations and others). The issue of train formation and optimisation from the point of view of a single railway station has been analysed by authors of works, e.g. [18, 23, 25, 36, 37]. In organising the operation of a single station, Ruf and Cordeau [37] identified four main optimisation issues (based on the work of [5, 6, 19]):

1. cut generation problem – for the case where the tracks of the arriving group are shorter than the arriving train, among the works considering this issue, one can point to e.g. [2, 6],
2. train makeup problem – for the allocation of wagons from arriving trains to departing trains, among the works considering this issue, one can point to e.g. [6, 29],
3. railcar classification problem – concerns the order in which wagons are marshalled, their allocation to specific tracks of a directional group, as well as the assignment of tasks to station resources; among the works considering this issue, one can indicate e.g. [34, 46],
4. outbound track assignment problem – train formation on several outbound tracks; among the works considering this issue, one can point out e.g. [7, 33, 46].

Ruf and Cordeau [37] presented a comprehensive method to optimise wagon marshalling in a one-step approach. In their work, they developed a station organisation model considering the four optimisation issues mentioned above. In addition, they included in the model aspects of scheduling, service allocation and ensuring station safety. They proposed a metaheuristic algorithm based on neighbourhood search to solve the formulated optimisation model. Other works considering these issues as an integrated problem include, for example [34, 35].

Gestrelius et al. [14] presented the issue of multistage train formation with mixed use of station tracks in their paper. They proposed an integer programming optimisation model for scheduling train formation by allocating individual arrival and directional tracks. They did not consider separate departure tracks in their work. On the other hand, Zhang et al. [46] also considered the problem with the possibility of multiple wagon marshalling, but in their work, they assumed that wagons are grouped and schedule the order and marshalling method according to the needs of train formation on the departure tracks. It is intended to reduce the number of marshalling and coupling operations and, through appropriate composition, increase the efficiency of the railway network. They proposed a binary model to represent the problem and developed an algorithm to solve it based on the metaheuristic method of tabu search. Research in the context of optimising the formation of trainsets at a marshalling yard with multistage sorting in terms of operational efficiency can also be found, for example, in the works [4, 3]. A detailed analysis of the current state of research in management and decision-making problems at shunting stations was presented in a paper by Deleplanque et al. [8].

The previously discussed work has mainly focused on formulating optimisation models to support decision-making regarding train marshalling strategies and the implementation of station processes in general. Although often complex and considering many aspects of hub railway stations, optimisation models are of limited use in the practical investigation and evaluation of station performance. Analytical models are often formulated to assess performance and capacity, but these are insufficient for a comprehensive assessment [45]. Hence, simulation methods are essential in organising and managing railway station processes.

As Baugher [1] points out, the time spent by trainsets at terminals and stations takes up 2/3 of their total time in running services, and 1/3 is the time spent moving them around the railway network. He further points out that many companies have experienced specialists in using methods and tools to manage and plan the movement of trainsets on the network, which cannot be indicated for railway terminals and stations. His work uses the AnyLogic tool to develop a simulation model of railway station processes. Dick [9] used another tool in his work, namely YardSYM. He analysed the flexibility of schedules and the varying volume of wagons moved on the railway network on the performance of a nodal railway station. Khadilkar and Sinha [25], on the other hand, proposed an approach to optimise timing operations precisely using simulation. They developed a model based on discrete event simulation in their approach. The objective of the optimisation was to minimise the time spent by the wagons from arrival at the arrival track group to their movement to the departure track group. A similar study in terms of optimisation using simulation was presented in the paper [38], where the sorting of trains and queuing them for marshalling operations were investigated. Galadíková and Adamko [12] also applied a simulation model to railway station management and work organisation. They used the Villon tool to support real-time decision-making by dispatchers. As they point out, the model they developed not only allows the evaluation of the decisions made and their consequences, but is also a helpful tool in the training of employees. In addition, simulation is often used in cargo operations at freight stations, especially in intermodal transport – the works of e.g. [20, 31, 32, 43] can be pointed out here. AnyLogic, FlexSim, YardSYM, YardSim, Optiyard, and Villon are the most frequently used simulation tools to support the planning, management and organisation of railway station operations, including processes at nodal stations.

Furthermore, the use of a simulation environment is the basis of digital twins, which in recent years have also been gaining popularity in railway transport in both academic and practical terms [13, 24, 39], as well as for the analysis of modern transport systems such as hyperloop [26]. These methods are also often combined with optimisation techniques, called optimisation by simulation and such an approach in the area of railway transport is used, for example, in the work of [42].

Based on the above review and other review works [6, 8], the literature on the subject is extensive and touches on various aspects of the organisation of railway freight transport, including station operation. Scientific works in the area of the organisation of the operation of nodal railway stations mainly focus on the marshalling strategy, the sequence of train handling or the determination of shunting locomotives' marshalling routes, and these issues are considered separately, and there is a lack of integrated approaches to decision support from the entry to the exit of the train from the station. At the same time, there is a lack of assessment models to compare solutions at different scales, organisations and tasks carried out in the station. Hence, this article presents a method that takes these issues into account and, at the same time, adds to the knowledge in this area.

3. CHARACTERISTICS OF THE TECHNOLOGICAL PROCESS OF WAGON PROCESSING

As defined in [40], processing is a set of technological activities related to realising the station work element. The implementation of these activities results from the nature of the station operation and technological needs. At nodal stations, the processing is mainly carried out on terminating and starting freight trains and wagons in transit and loco wagons. Each handling stage may be carried out on dedicated tracks for the relevant group, depending on the station layout and organisation. The technological process is a set of activities related to the processing of trains and is developed for each group of tracks (e.g., arrival, directional, departure) and technical teams that make up the station technological process (STP).

The broad range of activities carried out at the nodal station is shown in Fig. 1, broken down into the process phases (receiving, marshalling, collation and departure). The activities in the station are carried out according to a prepared schedule. For each group of tracks or marshalling yards, schedules are drawn up with a breakdown of the activities to be performed and their duration, start time and relationship to each other. These schedules should consider the activities' parallelism to minimise the time spent by the train/wagon in the station area. However, this also depends on the station's technical and human resources.

The execution of activities in nodal railway stations causes units (related to the tasks to be handled) such as trains, trainsets, wagons, uncouplers, and groups of wagons to be moved within the station. These units are formed by combining, splitting, or transforming in different configurations depending on the process's stage [11, 15, 21].

In principle, the components mentioned above of the technological process concerning a given train occur in the order indicated above. Occasionally, a situation may arise where the technological process is started from a different point than the acceptance of the trainset (e.g., during the execution of the train set process). Consequently, if one constituent element has not finished, the next cannot start [28].

In order to carry out the above process components, shunting work is required, which includes any shunting with wagons, groups of wagons, or preparing a trainset for movement on the railway network.

4. THE METHOD FOR ASSESSING THE TECHNOLOGICAL PROCESS OF WAGON PROCESSING AT THE SHUNTING STATION

4.1. Assumptions

The article addresses the issue of evaluating the technological process of wagon processing at the shunting station. For this purpose, an evaluation method was proposed using a simulation model and developed process evaluation measures. The developed process evaluation method follows four main stages. Its diagram is shown in Fig. 2.

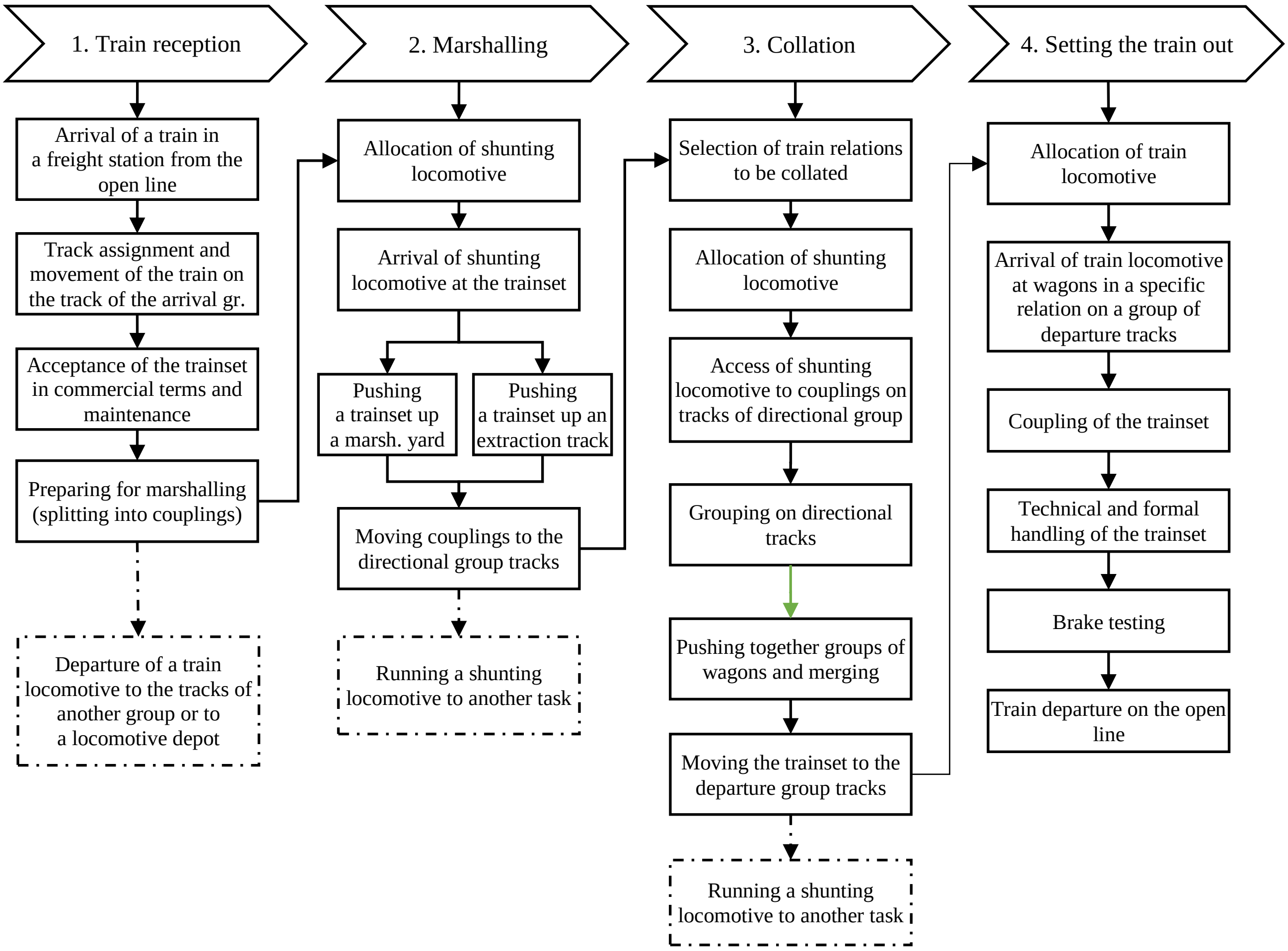


Fig. 1. Diagram of the processing of a freight train according to the phases of the process of passing through a nodal station

The first stage of the method is establishing the research's assumptions. For the research, the following assumptions were made.

- The research aims to demonstrate the potential and practical applicability of the developed method based on the simulation model and the developed process evaluation measures. The developed example includes different variants of the organisation.
- A shunting station modelled on an existing facility, with a one-way layout with a marshalling yard and groups of arrival, directional, departure and transit tracks, will be assessed. It is shown schematically in Fig. 3.
- Two entries sources are adopted: WE_ST – for terminating trains and transit trains with processing (wagon replacement or wagon uncoupling) and WE_LOCO_TR for wagon trainsets from loading points, transit wagons from the previous day, transit trains without processing and with processing with wagon coupling. There are also two outputs, WY_ST for trains starting at a station and for transit trains, and WY_LOCO_TR for wagon trainsets moved to load points and for wagons in transit destined for trains in subsequent days.
- The time horizon for the research and simulation is one day (00:00 – 24:00).

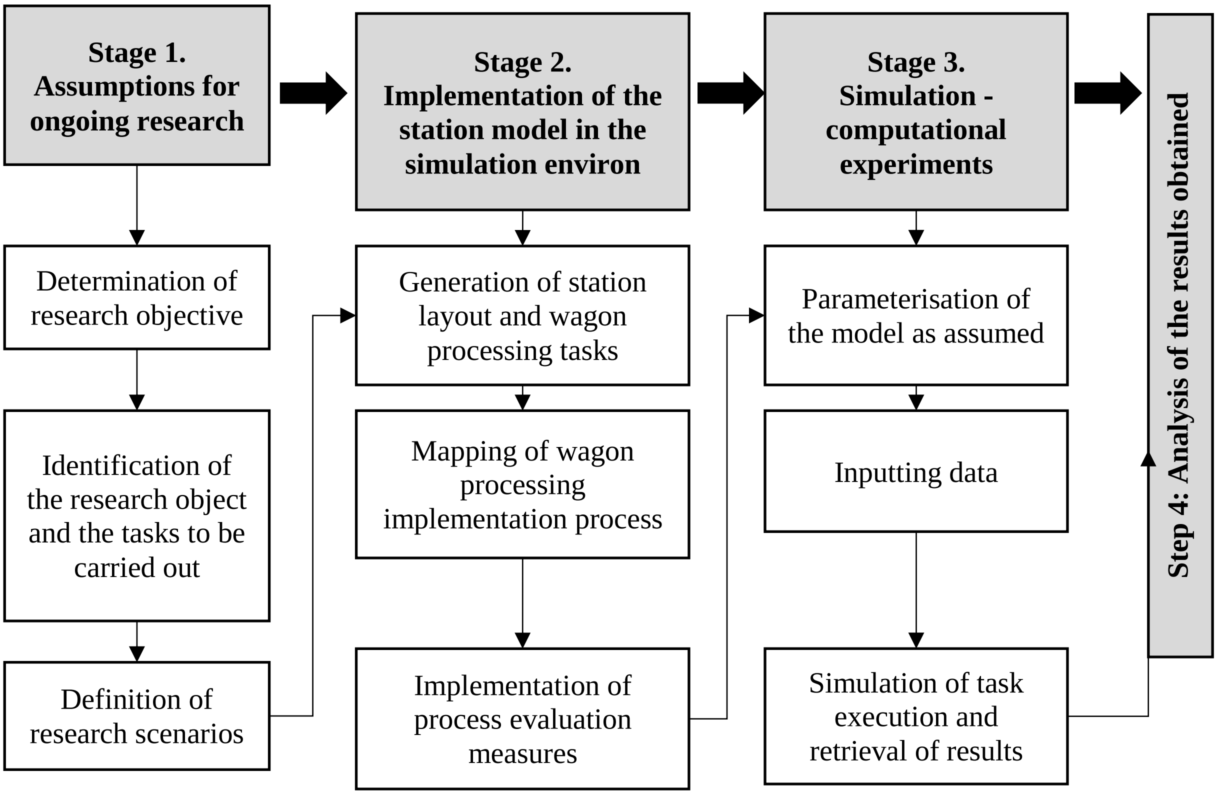


Fig. 2. The method for assessing the technological process of wagon processing at the shunting station

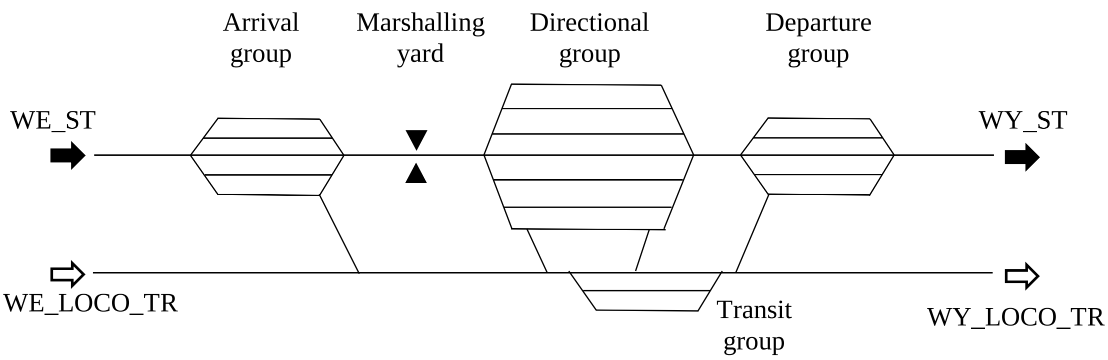


Fig. 3. Schematic layout of the station mapped as a simulation model

- Due to the nature of the simulation study, the input data on the number of trains and their composition will be generated randomly, considering constraints on the length of the trainset and considering different directions and wagon relations.
- Simulation studies are carried out to determine the impact of the number of shunting locomotives used and the organisation of the arrival and departure of trains on the processes carried out. Four test scenarios were adopted in the example developed, considering two organisational changes. The first is using a different number of locomotives (one or two shunting locomotives), and the second change is the arrival and departure times of the trains.

In one case, the times will be random and will not meet the condition of ensuring a minimum transition time for a wagon between the arrival and departure trains. In the other case, the arrival and departure times will consider this condition. On this basis, results will be obtained for four variants: V11, V12, V21, V22.

The second stage is implementing the shunting station model in a simulation environment. The chosen environment for the implementation of the research is FLEXSIM [10]. It is a powerful process research tool based on event-driven simulation. It contains an extensive library of functional elements such as queues, processors, conveyors, and operators. Additional relevant modules include the 'Process flow' module for mapping process flows in block form, the experimenter module for investigating various scenarios, and the OptQuest module for process optimisation. In addition, it enables the creation of graphs based on simulation results. The FlexScript language, whose syntax is similar to C++, is used for programming in the Flexsim environment. This environment is readily used in practice but also in scientific work.

In studying objects such as shunting stations, a common problem is acquiring actual data due to their secrecy. For this reason, data generators make it possible to prepare a model and input data for simulation based on assumptions and expert knowledge. A generator for the layout of stations, wagons, and input and output trains was prepared as part of the work. The logic of the simulation model was then developed, specifying the detailed process flow from the train's arrival at the station to its departure. A discussion of the simulation model logic is presented in section 4.2. The final element of this stage is the implementation of the evaluation measures, which are presented in section 4.3. Stages 3 and 4, i.e., the simulations and their results, are presented in section 5.

4.2. Implementation of the station model in the simulation environment - model logic

As indicated in the previous section, a generator for the layout of stations, wagons, and trains, including the entry and exit times of trains, was prepared as part of the implementation. The generators result in a mapped station track layout, as well as data:

- wagons – data: wagon number, input train number, output train number, wagon route type, planned wagon entry time, planned wagon exit time, output train number,
- entrance trains – data: entrance train number, entrance moment, entrance train type, number of wagons, wagon numbers in the train,
- exit trains – data: entrance train number, the planned moment of exit, type of entrance train, number of wagons, numbers of wagons in the train.

The next element is the development of the model logic, i.e., the representation of the processes for the passage of the wagons through the marshalling yard. The model logic was developed in the "Process flow" model in the Flexsim environment. Due to the extensive nature of this element, a diagram is presented for illustrative purposes in Fig. 4, with the main areas discussed below.

The first area is initialisation (1), i.e., zeroing the result tables and preparing the simulation model for operation. The following elements are the generation of input and output train 'tokens', i.e., markers that trigger particular activities. The generated tokens trigger, at the appropriate moment (according to the plan), activities related to the train's appearance at the station entrance and activities determining the possibility of the train leaving the station. Also included is an area responsible for allocating resources, i.e., individual groups of tracks, marshalling yards and shunting locomotives, and notification lists for trains and wagons.

In addition, procedures responsible for the collection of results are also defined. The generator tokens go to further activities, subdivided by train types or wagon routes. Tokens representing incoming trains go to the area (2). These areas are responsible for handling trains arriving at the station. Once the trains have been identified, they are received on the relevant arrival group or transit tracks. Other train and wagon handling activities are performed depending on the train and wagon route type. These also include the departure of the trainsets to the WY_LOCO_TR output, i.e., to the loading points. The next area is responsible for sending trains to the open line (3). Once the condition of collecting all wagons planned to be sent out in a given train is fulfilled, it is put together on the tracks of the departure group or joined to a transit train. Technical and commercial handling of the formed trainset occurs and is set out if there is already a departure report. The train can be launched on time or late. The model does not provide for an earlier departure than scheduled.

The logic developed adopts the First-In-First-Out (FIFO) principle, meaning that system resources to handle incoming requests are allocated according to the order of appearance. It should be emphasised that this strategy is inefficient in an existing facility. This approach was adopted only to validate the developed method. In the model, it was ensured that only one shunting locomotive could be present in the marshalling yard and on a given connection. In addition, it has been assumed that the service times are determined as average values. However, it is possible to adopt random variable values and thus represent the actual processes more faithfully.

4.3. Process evaluation measures

The simulation model allows statistics to be collected on the time taken to occupy resources or the distance travelled by the locomotive. It is essential information for evaluating individual process elements. However, it was considered that they are not sufficient and do not give a complete picture of the realisation of technological processes. Therefore, a synthetic criterion *FS* was developed, consisting of the sub-criteria *FKwag*, *FKloc*, *FKrail* and *FKorg*. A selection of these sub-criteria comprises the evaluation measures. Schematically, the layout of the measures is shown in Fig. 5. Both measures and sub-criteria require the determination of their weight in the evaluation, which can be determined by surveys or expert interviews (α for criteria, β for measures). In this article, they are defined expertly.

The criteria developed allow the technological process of wagon processing at the shunting station to be evaluated on a scale of 0-1. The higher the value, the better the implementation of the evaluation. Both the synthetic criterion and the sub-criteria and measures are expressed on this scale. This approach makes it possible, on the one hand, to clearly observe the impact the introduced changes have on the process and, on the other hand, to globally compare solutions with different tasks and scales precisely based on the *FS* criterion.

Assuming the above arrangement of criterion functions and measures, the synthetic criterion can be written as:

$$FS = \left[FKwag \cdot \alpha_{wag} + FKloc \cdot \alpha_{loc} + FKrail \cdot \alpha_{rail} + FKorg \cdot \alpha_{org} \right] \tag{1}$$

whereby the system of equations defining the assumed weights must be satisfied:

$$\begin{cases} \alpha\_wag + \alpha\_lokm + \alpha\_tor + \alpha\_org + \alpha\_ukl = 1 \\ 0 \le \alpha\_wag, \alpha\_lokm, \alpha\_tor, \alpha\_org, \alpha\_ukl \le 1 \end{cases} \tag{2}$$

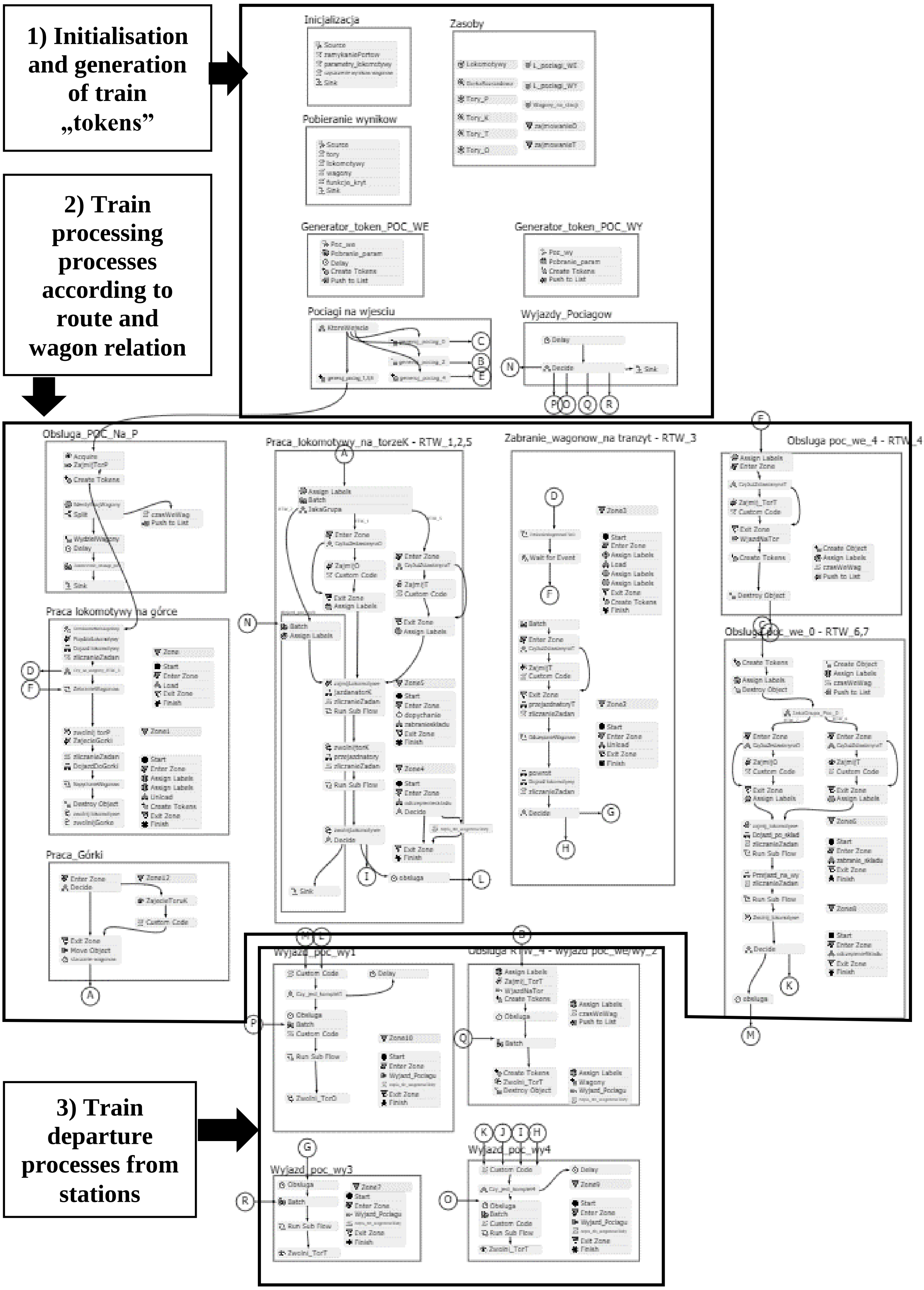


Fig. 4. Simulation model logic in the Flexsim environment

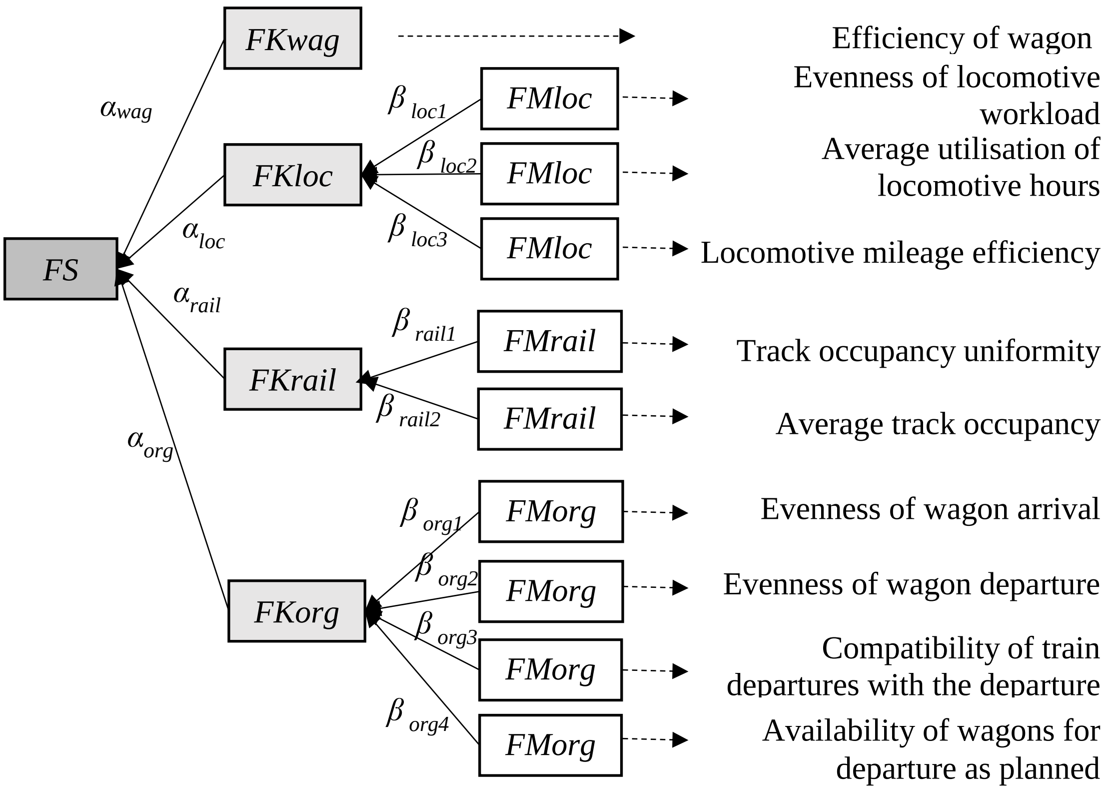


Fig. 5. Layout of process evaluation measures for wagon processing

The following components of the synthetic criterion have the following interpretations:

- *FKwag* – which determines the extent to which station capacity is used in terms of carrying out the technological process of wagon processing. This indicator is based on the duration of individual activities on a wagon concerning the minimum times set for the station.
- *FKloc* – which assesses the use of shunting locomotives. It consists of three measures. Measure *FMloc1* is the uniformity of shunting locomotive workload distribution. It is defined as the difference between the maximum locomotive utilisation rate (among all locomotives) and the average locomotive utilisation rate. Measure *FMloc2* is the average locomotive time utilisation. Measure *FMloc3* is the locomotive's mileage efficiency. It is defined as the product of the minimum distance needed to complete a task by the distance travelled by the locomotive, considering the actual marshalling. This measure is weighted by the number of locomotive tasks concerning the number of wagons that pass through the station. Taking this sub-criterion into account, it takes the form:

$$FKloc = \left[FMloc1 \cdot \beta_{loc1} + FMloc2 \cdot \beta_{loc2} + FMloc3 \cdot \beta_{loc3} \right] \tag{3}$$

whereby:

$$\begin{cases} \beta_{loc1} + \beta_{loc2} + \beta_{loc3} = 1 \\ 0 \le \beta_{loc1}, \beta_{loc2}, \beta_{loc3} \le 1 \end{cases} \tag{4}$$

– *FKrail* – which makes it possible to assess the use of tracks at a station. It consists of two measures. Measure *FMrail1* is the uniformity of track occupancy, defined as the ratio of the average track occupancy at the station and the maximum track occupancy. Measure *FMrail2* is the average track occupancy per day. Given the above, the sub-criterion takes the form:

$$FKrail = \left[FMrail1 \cdot \beta_{rail1} + FMrail2 \cdot \beta_{rail2}\right] \tag{5}$$

whereby:

$$\begin{cases} \beta_{rail1} + \beta_{rail2} = 1 \\ 0 \le \beta_{rail1}, \beta_{rail2} \le 1 \end{cases} \tag{6}$$

– *FKorg* – which assesses the train arrival and departure plan for the station's work organisation. It consists of four measures. Measure *FMorg1* is the uniformity of wagon arrivals, which should be understood as the distribution of the number of wagons arriving at the station daily. Measure *FMorg2* is the uniformity of wagon departures per day. Measure *FMorg3* is the consistency of trainsets departing from a station with the departure plan, defined as the ratio of trains departing on time to the number of all trains departing in a day. Measure *FMorg4* is the availability of wagons to be discharged as planned. It is a value averaged over all the wagons being expedited from the station. It considers the minimum time needed to process a wagon at the station and the difference between the arrival of the wagon and the planned departure. If the wagon's planned departure time is less than the sum of the processing time and the wagon's arrival time, it is assumed that its availability is ensured. This measure is expressed by the product of the available wagons to all the departed wagons from the station. The sub-criterion takes the form:

$$FKorg = \left[FMorg1 \cdot \beta_{org1} + FMorg2 \cdot \beta_{org2} + FMorg3 \cdot \beta_{org3} + FMorg4 \cdot \beta_{org4}\right] \tag{7}$$

whereby:

$$\begin{cases} \beta_{org1} + \beta_{org2} + \beta_{org3} + \beta_{org4} = 1 \\ 0 \le \beta_{org1}, \beta_{org2}, \beta_{org3}, \beta_{org4} \le 1 \end{cases}. \tag{8}$$

5. VARIANT SIMULATION OF THE WAGON PROCESSING

5.1. Input data

Using the method developed, a simulation of the wagon processing was carried out, for example, taking into account the following data:

– number of tracks: P – arrival (12), K – directional (20), O – departure (12), T – transit (12),
– track length: 800 m (P, K, T groups), 1000 m (O groups),
– average shunting locomotive speed: 12 km/h (unloaded), 5 km/h (pushing), 8 km/h (switching wagons),
– wagons and trains: 1000 (number of wagons per day), the minimum number of wagons per train (15), and the maximum number of wagons per train (50).

According to the assumptions, four variants of organisation and, thus, four simulation scenarios were adopted, i.e., V11, V12, V21, and V22. The differences between the adopted variants concern only the number of shunting locomotives and the condition for the minimum wagon passage time (see Tab. 1). For the assessment of the individual variants, selected sub-criteria and metrics were adopted, the weights of which were expertly established as: α_{wag} = 0,35, α_{loc}= 0,15, α_{rail}= 0,1, α_{org}= 0,4, β_{loc1}= 0,2, β_{loc2}= 0,6, β_{loc3}= 0,2, β_{rail1}= 0,3, β_{rail2}= 0,7, β_{org1}= 0,15, β_{org2}= 0,15, β_{org3}= 0,5, β_{org4}= 0,2.

Tab. 1

Calculation scenarios

Data description	**V11**	**V12**	**V21**	**V22**
Number of shunting locomotives	1	1	2	2
Meeting the condition for minimum wagon passage time	0	1	0	1

Based on the data entered, a track network was generated at the railway station, as shown in Fig. 6. The simulation time was 24 h, according to the model assumptions.

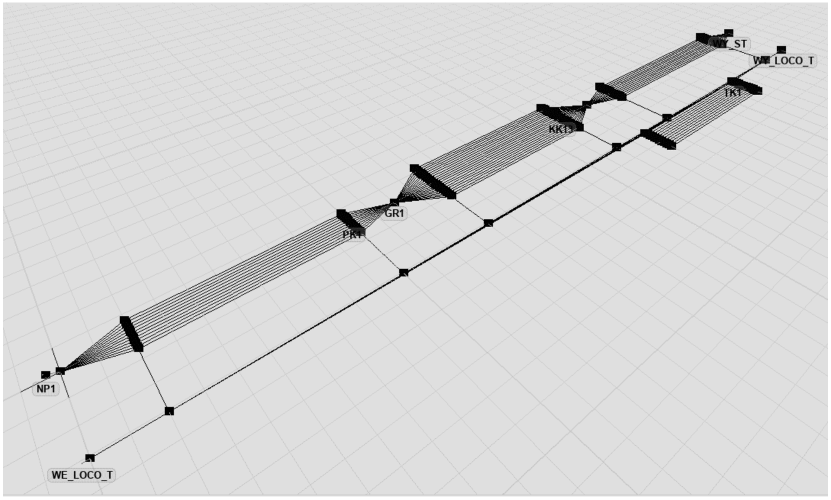


Fig. 6. Generated railway station track network for simulation and calculation of V11, V12, V21, and V22 options

5.2. Simulation results and analysis of results

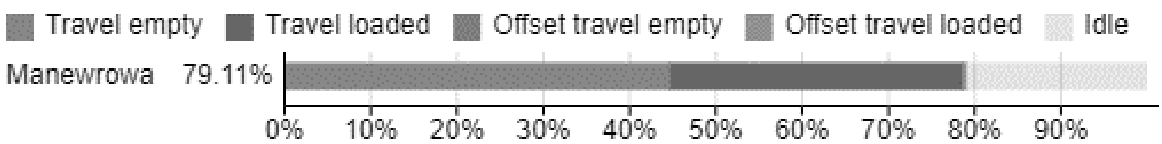
The simulations made it possible to determine the values of the unit measures of station performance evaluation, i.e., for each wagon, train, track, and locomotive, under the requirements for determining the values of the partial and synthetic criteria. Due to the extensiveness of the data, the results of the calculations are presented for the previously discussed measures, sub-criteria and synthetic criterion (Tab. 2.). A locomotive working diagram was generated showing the proportion of activities performed during working time, including running time with wagons, slack time and idle time (Fig. 7).

Tab. 2

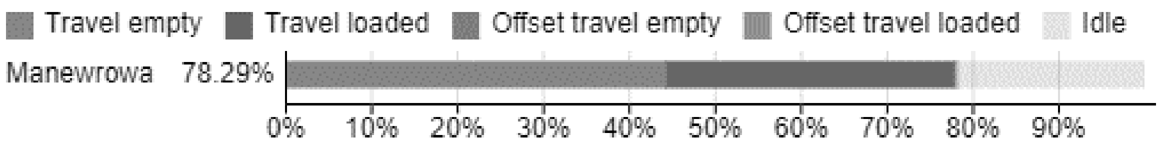
Results of task and station performance evaluation for options V11, V12, V21, V22

	V11	**V12**	**V21**	**V22**
FKwag	0,17	0,18	0,27	0,19
FMloc1	1	1	1	0,99
FMloc2	0,79	0,78	0,57	0,57
FMloc3	0,38	0,38	0,18	0,19
FKloc	0,75	0,744	0,578	0,578
FMrail1	0,33	0,26	0,23	0,22
FMrail2	0,33	0,38	0,24	0,33
FKrail	0,33	0,34	0,24	0,3
FKrail1	0,24	0,24	0,24	0,24
FKrail2	0,22	0,18	0,35	0,28
FKrail3	0,11	0,32	0,09	0,21
FKrail4	0,67	1	0,67	1
FKorg	0,258	0,423	0,2675	0,383
FS	**0,3082**	**0,3778**	**0,3122**	**0,3364**

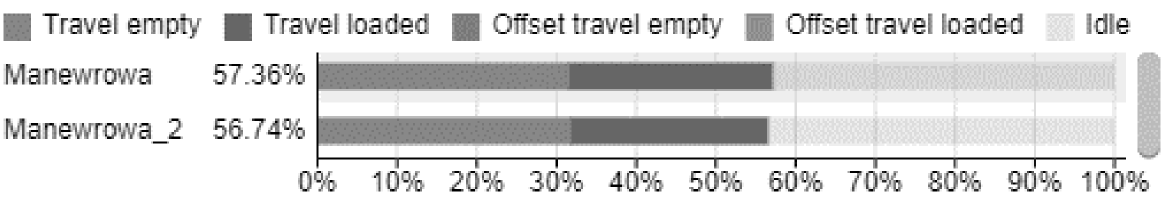
V11 – one locomotive, no condition for minimum wagon transit time



V12 – one locomotive, with a condition for minimum wagon transit time



V21 – two locomotives, no condition for minimum wagon transit time



V22 – two locomotives, with a condition for minimum wagon transit time

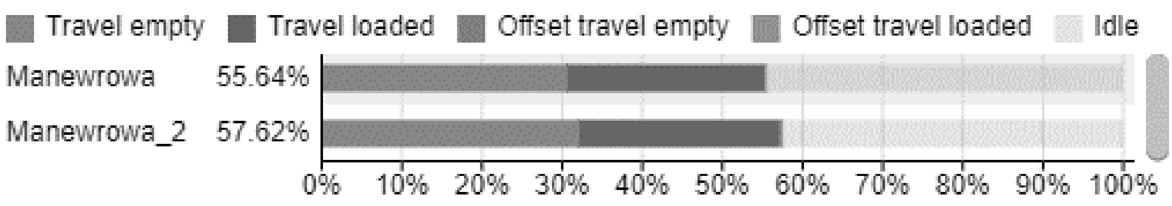


Fig. 7. Locomotive performance graph and share of activities for V11, V12, V21, V22

In the example developed, from the point of view of the *FKwag* criterion for wagon transit time to the minimum transit time, V21 proved to be the best option, in which the work is carried out by two locomotives and at the same time, the departure plan does not take into account the minimum wagon transit time through the station. It results in a greater variety of arrival and departure tasks and has made it possible to achieve shorter wagon waiting times for processing. Regarding the *FKloc* criterion, variant V11 is the best, and variant V12 is slightly worse, these are the variants with one locomotive, and its utilisation is the best. The variants with two locomotives proved significantly worse in this respect due to the task allocation strategy and the lack of separation of the shunting zones of their work.

It means that locomotives can be allocated to work on, for example, a marshalling yard and waiting for the other locomotive to complete the task is necessary. A solution to improve this element would be to separate locomotive work zones or a different task allocation strategy. Regarding the *FKrail* criterion, the best option was V12, which seeks the best possible use of the infrastructure and uniformity of loading. However, load uniformity is also influenced by the organisation of train arrivals and departures. In the *FKorg* criterion, V12 again emerged as the best option.

When analysing the variants, it should be noted that a significant change was the introduction of a modification in the form of changing the train departure time and ensuring at least a minimum time interval from the wagon's entry into the station to its exit from the station, taking into account all processing operations on the different track groups. It had a noticeable effect on the *FS* value, and the variants with one or two locomotives proved the best.

However, when comparing the impact of the change in the number of locomotives, it should be noted that, as one locomotive is sufficient to handle all requests, in this case, the change did not significantly affect the final evaluation result, and indeed in the case of the V12, which proved to be the best option, one locomotive compared to V22 is an improvement. It is due to the task mentioned above, allocation and the ability to block work. A significant influence on the final *FS* score was the timeliness of the train out, and consequently, the considerable inconsistency in this area was precisely due to the inability to complete all the activities in a shorter time. It affects the outcome of the assessments of V11 and V21.

Analysing the individual criteria and the *FS* value, it should be pointed out that the result is mainly influenced by the *FIFO* strategy adopted and the random generation of trains (the selected trains and the sequence of incoming and outgoing trains may be unjustified). In practice, an assignment strategy based on the arrival and departure plan of trains should be implemented, which would make it possible to reduce the case of blocked tracks or shunting locomotives.

6. SUMMARY

This paper aims to present the author's process evaluation approach for assessing the technological process of freight wagon processing at shunting stations. The developed method formulated measures, sub-criteria and a synthetic criterion for evaluating the processing and station operation on a scale of 0-1. This unique approach allows the identification of critical areas of the station and stages of the wagon processing, while simultaneously enabling the comparison of different solutions at different scales.

The realised computational example shows the great potential of the method and its wide range of possibilities in both research and practical terms. Decision-makers can use the method to evaluate the organisation of processes and assess the fit between the station layout and the tasks at hand.

Potential areas for further work and extensions of the developed method were identified based on the research. Among these, it is essential to point out the following:

- research and consideration of safety aspects and the impact of the station on the surroundings,
- consideration of different wagon marshalling and train formation strategies,
- study of ways to organise train arrivals and departures,
- extension of the method to include the issue of human labour and the assignment of workers to tasks,
- extension of the method to include process elements related to loading operations at station loading points.

References

1. Baugher Roger W. 2015. Simulation of Yard and Terminal Operations. In: *Handbook of Operations Research Applications at Railroads* 222: 219-42. Edited by Bruce W. Patty. International Series in Operations Research & Management Science. Boston, MA: Springer US. DOI: https://doi.org/10.1007/978-1-4899-7571-3_9.
2. Bohlin Markus, Florian Dahms, Holger Flier, Sara Gestrelius. 2012. „Optimal Freight Train Classification Using Column Generation". Application/pdf. DOI: https://doi.org/10.4230/OASICS.ATMOS.2012.10.
3. Bohlin Markus, Ronny Hansmann, Uwe T. Zimmermann. 2018. Optimization of Railway Freight Shunting. In: *Handbook of Optimization in the Railway Industry* 268: 181-212. Edited by Ralf Borndörfer, Torsten Klug, Leonardo Lamorgese, Carlo Mannino, Markus Reuther, Thomas Schlechte. International Series in Operations Research & Management Science. Cham: Springer International Publishing. DOI: https://doi.org/10.1007/978-3-319-72153-8_9.
4. Bohlin Markus, Sara Gestrelius, Florian Dahms, Matúš Mihalák, Holger Flier. 2016. „Optimization Methods for Multistage Freight Train Formation". *Transportation Science* 50(3): 823-40. DOI: https://doi.org/10.1287/trsc.2014.0580.
5. Boysen Nils, Malte Fliedner, Florian Jaehn, Erwin Pesch. 2012. „Shunting Yard Operations: Theoretical Aspects and Applications". *European Journal of Operational Research* 220(1): 1-14. DOI: https://doi.org/10.1016/j.ejor.2012.01.043.
6. Boysen Nils, Simon Emde, Malte Fliedner. 2016. „The Basic Train Makeup Problem in Shunting Yards". *OR Spectrum* 38(1): 207-33. DOI: https://doi.org/10.1007/s00291-015-0412-0.
7. Caimi Gabrio, Frank Fischer, Thomas Schlechte. 2018. Railway Track Allocation. In: *Handbook of Optimization in the Railway Industry* 268: 141-59**.** Edited by Ralf Borndörfer, Torsten Klug, Leonardo Lamorgese, Carlo Mannino, Markus Reuther, Thomas Schlechte. International Series in Operations Research & Management Science. Cham: Springer International Publishing. DOI: https://doi.org/10.1007/978-3-319-72153-8_7.
8. Deleplanque Samuel, Pierre Hosteins, Paola Pellegrini, Joaquin Rodriguez. 2022. „Train Management in Freight Shunting Yards: Formalisation and Literature Review". *IET Intelligent Transport Systems* 16(10): 1286-1305. DOI: https://doi.org/10.1049/itr2.12216.

9. Dick C. Tyler. 2021. „Influence of Mainline Schedule Flexibility and Volume Variability on Railway Classification Yard Performance”. *Journal of Rail Transport Planning & Management* 20 (December): 100269. DOI: https://doi.org/10.1016/j.jrtpm.2021.100269.
10. Flexsim. Available at: https://www.flexsim.com/flexsim/.
11. Gajda Bronisław. 1966. *Stacje rozrządowe*. Warszawa: Wydawnictwo Komunikacji i Łączności. [In Polish: *Marshalling stations*. Warsaw: Transport and Communication Publishers].
12. Galadíková Andrea, Norbert Adamko. 2021. „Simulation-Based Methods to Support the Real-Time Management of Railways Nodes”. *Transportation Research Procedia* 55: 1345-52. DOI: https://doi.org/10.1016/j.trpro.2021.07.119.
13. Gao Yan, Shuyue Qian, Zihan Li, Ping Wang, Feiyue Wang, Qing He. 2021. „Digital Twin and Its Application in Transportation Infrastructure”. In: *2021 IEEE 1st International Conference on Digital Twins and Parallel Intelligence (DTPI)*: 298-301. Beijing, China: IEEE. DOI: https://doi.org/10.1109/DTPI52967.2021.9540108.
14. Gestrelius Sara, Martin Aronsson, Martin Joborn, Markus Bohlin. 2017. „Towards a Comprehensive Model for Track Allocation and Roll-Time Scheduling at Marshalling Yards”. *Journal of Rail Transport Planning & Management* 7(3): 157-70. DOI: https://doi.org/10.1016/j.jrtpm.2017.06.002.
15. Gołębiowski Piotr, Ignacy Góra, Yaroslav Bolzhelarskyi. 2023. „Risk Assessment in Railway Rolling Stock Planning”. *Archives of Transport* 65(1): 137-54. DOI: https://doi.org/10.5604/01.3001.0016.2817.
16. Gołębiowski Piotr, Jacek Kukulski. 2020. „Preliminary Study of Shaping the Railway Track Geometry in Terms of Their Maintenance Costs and Capacity”. *Archives of Transport* 53(1): 115-28. DOI: https://doi.org/10.5604/01.3001.0014.1787.
17. Gołębiowski Piotr, Marianna Jacyna, Andrzej Stańczak. 2021. „The Assessment of Energy Efficiency Versus Planning of Rail Freight Traffic. A Case Study on the Example of Poland”. *Energies* 14: 1-18. DOI: https://doi.org/10.3390/en14185629.
18. Haahr Jørgen Thorlund, Richard Martin Lusby. 2016. „A Matheuristic Approach to Integrate Humping and Pullout Sequencing Operations at Railroad Hump Yards”. *Networks* 67(2): 126-38. DOI: https://doi.org/10.1002/net.21665.
19. He Shiwei, Rui Song, Sohail S. Chaudhry. 2003. „An Integrated Dispatching Model for Rail Yards Operations”. *Computers & Operations Research* 30(7): 939-66. DOI: https://doi.org/10.1016/S0305-0548(02)00064-3.
20. Jachimowski Roland, Emilian Szczepański, Michał Kłodawski, Katarzyna Markowska, Janusz Dąbrowski. 2018. „Selection of a Container Storage Strategy at the Rail-Road Intermodal Terminal as a Function of Minimization of the Energy Expenditure of Transshipment Devices and CO_2 Emissions”. *Rocznik Ochrona Środowiska* 20: 965-988.
21. Jacyna Marianna, Piotr Gołębiowski, Mirosław Krześniak, Janusz Szkopiński. 2019. *Organizacja ruchu kolejowego*. Warszawa: Wydawnictwo Naukowe PWN SA. [In Polish: *Organisation of railway traffic*. Warsaw: Scientific Publishers PWN SA].
22. Jacyna Marianna, Mirosław Krześniak. 2018. Computer Support of Decision-Making for the Planning Movement of Freight Wagons on the Rail Network. In: *Recent Advances in Traffic Engineering for Transport Networks and Systems* 21: 225-236. Edited by Elżbieta Macioszek, Grzegorz Sierpiński. DOI: https://doi.org/10.1007/978-3-319-64084-6_21.
23. Jaehn Florian, Johannes Rieder, Andreas Wiehl. 2015. „Minimizing Delays in a Shunting Yard”. *OR Spectrum* 37(2): 407-29. DOI: https://doi.org/10.1007/s00291-015-0391-1.

24. Kaewunruen Sakdirat, Jessada Sresakoolchai, Yi-hsuan Lin. 2021. „Digital Twins for Managing Railway Maintenance and Resilience". *Open Research Europe* 1 (November): 91. DOI: https://doi.org/10.12688/openreseurope.13806.2.
25. Khadilkar Harshad, Sudhir Kumar Sinha. 2016. „Rule-Based Discrete Event Simulation for Optimising Railway Hump Yard Operations". In: *2016 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM)*: 1151-55. Bali, Indonesia: IEEE. DOI: https://doi.org/10.1109/IEEM.2016.7798058.
26. Kowal Barbara, Robert Ranosz, Michal Klodawski, Roland Jachimowski, Janusz Piechna. 2022. „Demand for Passenger Capsules for Hyperloop High-Speed Transportation System – Case Study From Poland". *IEEE Transactions on Transportation Electrification* 8(1): 565-89. DOI: https://doi.org/10.1109/TTE.2021.3120536.
27. Kukulski Jacek, Konrad Lewczuk, Ignacy Góra, Mariusz Wasiak. 2023. „Methodological Aspects of Risk Mapping in Multimode Transport Systems". *Eksploatacja i Niezawodność – Maintenance and Reliability* 25: 1-11. DOI: https://doi.org/10.17531/ein.2023.1.19.
28. Kushakova Mamura Narimanovna. 2022. „Increasing the Efficiency of Logistics Management in Railway Transport". *ACADEMICIA: An International Multidisciplinary Research Journal* 12(2): 342-46. DOI: https://doi.org/10.5958/2249-7137.2022.00142.2.
29. Li Haodong, Rui Song, Mingzhou Jin, Shiwei He. 2014. „Optimization of Railcar Connection Plan in a Classification Yard". In: *TRB 93rd Annual Meeting Compendium of Papers*. Washington DC, USA.
30. Matsiuk Viacheslav. 2017. „A study of the technological reliability of railway stations by an example of transit trains processing". *Eastern-European Journal of Enterprise Technologies* 1(3): 18-24.
31. Mohammad Hasany, Reza, Kian Rastegar. 2022. „Simulation of Container Operations in the Marshaling Yard – Case Study: Aprin Station". *International Journal of Railway Research* 9(1): 1-10. DOI: https://doi.org/10.22068/ijrare.293.
32. Nehring Karol, Michał Kłodawski, Roland Jachimowski, Piotr Klimek, Rostislav Vašek. 2021. „Simulation Analysis of the Impact of Container Wagon Pin Configuration on the Train Loading Time in the Intermodal Terminal". *Archives of Transport* 60(4): 155-69. DOI: https://doi.org/10.5604/01.3001.0015.6928.
33. Otto Alena, Erwin Pesch. 2019. „The Train-to-Yard Assignment Problem". *OR Spectrum* 41(2): 549-80. DOI: https://doi.org/10.1007/s00291-019-00547-y.
34. Preis Henning, Stefan Frank, Sebastian Bäcker, Rainer König. 2018. „Optimizing Production Schedules in Classification Yards". *Proceedings of 7th Transport Research Arena TRA* 16: 19.
35. Raut Sumit, Sudhir Kumar Sinha, Harshad Khadilkar, Shripad Salsingikar. 2019. „A Rolling Horizon Optimisation Model for Consolidated Hump Yard Operational Planning". *Journal of Rail Transport Planning & Management* 9: 3-21. DOI: https://doi.org/10.1016/j.jrtpm.2018.09.002.
36. Rinaldi Franca, Romeo Rizzi. 2017. „Solving the Train Marshalling Problem by Inclusion–Exclusion". *Discrete Applied Mathematics* 217: 685-90. DOI: https://doi.org/10.1016/j.dam.2016.09.044.
37. Ruf Moritz, Jean-François Cordeau. 2021. „Adaptive Large Neighborhood Search for Integrated Planning in Railroad Classification Yards". *Transportation Research Part B: Methodological* 150: 26-51. DOI: https://doi.org/10.1016/j.trb.2021.05.012.

38. Saeednia Mahnam, Dirk Bruckmann, Ulrich Weidmann. 2015. „Event-Based Model for Optimizing Shunting Yard Operations”. *Transportation Research Record: Journal of the Transportation Research Board* 2475(1): 90-94. DOI: https://doi.org/10.3141/2475-11.
39. Shubinsky Igor Borisovich, Alexei Mikhailovitch Zamyshlaev. 2022. Resource Management of Railway Transport Facilities. In *Technical Asset Management for Railway Transport* 322: 113-40. Edited by Igor Borisovich Shubinsky, Alexei Mikhailovitch Zamyshlaev. International Series in Operations Research & Management Science. Cham: Springer International Publishing. DOI: https://doi.org/10.1007/978-3-030-90029-8_7.
40. Szaciłło Lucyna, Marianna Jacyna, Emilian Szczepański, Mariusz Izdebski. 2021. „Risk Assessment for Rail Freight Transport Operations”. *Eksploatacja i Niezawodność – Maintenance and Reliability* 23(3): 476-88. DOI: https://doi.org/10.17531/ein.2021.3.8.
41. Yaghini Masoud, Mohsen Momeni, Mohammadreza Sarmadi. 2013. „An Improved Local Branching Approach for Train Formation Planning”. *Applied Mathematical Modelling* 37(4): 2300-2307. DOI: https://doi.org/10.1016/j.apm.2012.05.016.
42. Yıldırım Mehmet Sinan, Mustafa Karaşahin, Ümit Gökkuş. 2021. „Scheduling of the Shuttle Freight Train Services for Dry Ports Using Multimethod Simulation – Optimization Approach”. *International Journal of Civil Engineering* 19(1): 67-83. DOI: https://doi.org/10.1007/s40999-020-00553-0.
43. Zabielska Aleksandra, Marianna Jacyna, Michał Lasota, Karol Nehring. 2023. „Evaluation of the Efficiency of the Delivery Process in the Technical Object of Transport Infrastructure with the Application of a Simulation Model”. *Eksploatacja i Niezawodność – Maintenance and Reliability* 25: 1-13. DOI: https://doi.org/10.17531/ein.2023.1.1.
44. Zalewski Paweł, Piotr Siedlecki, Arkadiusz Drewnowski. 2005. *Technologia transportu kolejowego*. Warszawa: Wydawnictwa Komunikacji i Łączności. [In Polish: *Railway transport technology*. Warsaw: Transport and Communication Publishers].
45. Zhang Licheng, Mingzhou Jin, Zhirui Ye, Haodong Li, David B. Clarke, Yanyan Wang. 2017. „Macrolevel Classification Yard Capacity Modeling”. *Transportation Research Record: Journal of the Transportation Research Board* 2608(1): 125-33. DOI: https://doi.org/10.3141/2608-14.
46. Zhang Yingqun, Rui Song, Shiwei He, Haodong Li, Xiaole Guo. 2018. „Optimization of Classification Track Assignment Considering Block Sequence at Train Marshaling Yard”. *Journal of Advanced Transportation* 2018: 1-11. DOI: https://doi.org/10.1155/2018/3802032.

Received 09.01.2023; accepted in revised form 30.03.2023