Influence of transport and logistics infrastructure of industrial enterprises on the efficiency of marshalling yards

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Abstract. The article considers the problems of interaction between marshalling yards and industrial enterprises under the conditions of uneven operations. The need for modelling of transport processes at marshalling yards and non-public tracks is revealed and grounded. Based on the conducted study, the authors offer recommendations to develop a simulation model for marshalling yard operations. This model being developed with the AnyLogic adaptive programming matches the structure and technological process of marshalling yards and freight point operations and provides the solution of a problem of optimizing the marshalling yard's handling capacity. The process approach taken will reduce transportation costs emerging in the maintenance of non-public tracks and provide for the freight transportation regularity.

1 Introduction

An analysis of the operation of marshalling yards and places of non-public use is a required component when drafting the Unified technological process for the operation of adjacent stations and industrial transport facilities [1]. When marshalling yards are not able to handle the incoming volume of service requests, the adjunction railway stations' technological process is disrupted, thus slowing down a wagon's turnover and failing to meet the planned targets. Wagons awaiting unloading have to be distributed to railway stations in the region, posing a grave threat to the movement of wagon flows on railway sections. In this situation, rolling stock is not being released at marshalling yards and non-public tracks (NPT), the engagement of tracks results in technological glitches in marshalling yard operations, extra shunting operations are carried out and JSC Russian Railways suffers significant losses due to the long days of wagon demurrage and late delivery of freight. When examining the capacity of a marshalling yard to handle freight volumes and the related changes in equipment and rolling stock utilisation, the deterministic nature of local operation and the design parameters of the whole transport system under study must be taken into account.

The studies of Russian scientists [2] highlight the great influence of freight traffic unevenness on the transportation process. Its non-deterministic nature was identified through the application of probability theory and methods of mathematical statistics by studying the nature of train make-up and building a deterministic-stochastic series [3]. Variations can also

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be caused by seasonal trends in goods production and consumption and have rather stable patterns. Fluctuations in wagon flows are due to a large variety of causes and are random in nature. Large losses in the operational and local work of marshalling yards occur due to the inability to quickly compare the planned volume of transport operations with the railway capacity. Transportation process modelling provides such an opportunity [4].

Series of articles written by foreign scientists [5,7-10,14] pay much attention to the role of sophisticated software packages being able to assess the algorithms of real transport systems' behaviour. At simulation, a model's structure should replicate the structure of a real object to the greatest extent possible, and the relations between its individual components are a reflection of its true relations. The model developed is verified in terms of its correct implementation, and calibrated, i.e. the data are collected and the accuracy of the model is examined, i.e. its validation is carried out. An important stage of work with the model is a computer experiment, which records the output values of the process under study at various values of key parameters. Complex experiments provide an opportunity to analyse the model sensitivity, assess the risks of managerial decisions and optimise parameter values so to achieve the model effective functioning and then the real object itself.

Many foreign researchers have considered models to drive vehicles with deterministic and stochastic elements in the distribution of values under study. Deterministic approaches imply that the input parameters (e.g. demand for transport services, transportation and travel time) are accurate values. These optimisation models have been used to rationally allocate unladen vehicles according to the given allocation rules. Loxton [6] presented a dynamic routing and scheduling model for goods wagon traffic within the rail network. This spatio-temporal model was applied to represent the movement of wagon flows to possible destinations across the overall rail network, considering the movement of freight for priority customers. Narisetty [11] introduced a model to optimise the assignment of heterogeneous unladen goods wagons as the best match between the working fleet at marshalling yards and a level of freight operations. Such a model allowed transportation costs to be optimised and delivery times to be strictly complied with. The model has been implemented at the Union Pacific Railroad and helped the company to achieve a significant reduction in its transportation costs. Sayarshad and Marler [12] presented the development of a fleet size analysis solution. Their analysis tool includes the optimization of rolling stock utilization, assessment of profitability from efficient freight movement and quality control of services provided to customers. In his mathematical model to optimise planning for the utilisation of a homogeneous rail wagon fleet in the industry, Sayarshad [13] proposes to minimise the sum of costs related to service quality and maximise profit calculated as the difference between revenues and total costs for the wagon operation.

When applied to the issue of national traffic process organisation, a formalised description of transportation processes within the system of planning, actual execution and forecasting of local operation volumes is possible with a systematic approach through the development of a mathematical model and, at its basis, an adequate simulation model. The following algorithm is offered to carry out this research:

- conducting ongoing statistical analysis of wagon flow movements and controlling the possibility of wagon delivery from the external network under conditions of changes in incoming and outcoming wagon flows;
- determination of wagon engagement at the places of non-public use in the operational mode and redistribution of work among the industrial facilities at marshalling yards;
- ongoing monitoring of the dispatchers' decisions and optimisation of the results.

2 Methods

Determining the optimal level of loading the freight zones is a task for mathematical programming with elements of uncertainty due to the random nature of wagon arrivals at marshalling yards and service time. In [2], this task is solved by minimizing the costs of wagon and loading-and-unloading machine demurrage.

Based on statistical data on wagon arrivals, it is found that daily fluctuations describe the law of normal distribution. The equation then has the form:

$$D = D_1(N_p, t_{dem}) + D_2(N_r, t_{mech}) - \lambda((N_{max} - (N_p x_1 + N_r x_2) \rightarrow min \quad (1)$$

where N_{max} - maximum possible volume of work at a freight zone, N_p- optimal permissible level of work at a freight zone, Nr - unloading capacity reserve of a freight zone, D_1 (N_p, t_{dem}) and D_2 (N_r, t_{mech}) - variable costs of work at a freight zone, t_{wai} – demurrage time of wagons waiting for delivery to a freight zone; t_{mech} – demurrage time of loading-and-unloading mechanisms while waiting for wagons to be delivered, x1 and x2 - uncertainty coefficients that must be multiplied by the planned work volume and the freight zone reserve to find the actual work volumes.

An analysis of the presented cost minimisation expression, considering the random factors that affect the operation of freight zones, makes it clear that there is no analytical solution to the equation. When modelling the operation of freight zones and the adjacent railway station by the Monte Carlo method, the following results were obtained: the D_1 (N_p, t_{dem}) and D_2 (N_r, t_{mech}) take the form:

$$D_1(N_p, t_{dem}) = C_{dem\ w} t_{wai} N_{wai} \quad (2)$$

$$D_2(N_p,\ t_{мех}) = C_{dem\ m} t_{mech} n_{mech} \quad (3)$$

where $C_{dem\ w}$– the cost of one wagon demurrage within 1 hour, considering the cost of freight mass given to the current costs; N_{wai} – the number of wagons waiting to be delivered onto the freight zone; $C_{dem\ w}$ – the cost of loading-and-unloading mechanism demurrage within 1 hour; nmech – the number of mechanisms serving the freight zone.

The service cycle of any request structurally includes several service phases, which in turn consist of elements where the simplest operations are executed in a certain sequence and with the known time spent. The initial basis elements are marked with αi and the finite elements with γi. All other phases βi are intermediate [3]. The basis elements include the engagement of technological lines at the goods yard for delivery to the freight zone (receiving-and-departure yard, the breaking-up system, marshalling yard, station bottlenecks), the finite ones are the station elements to departure trains to the railway network (freight-handling equipment for loading-and-unloading zones, the make-up system, marshalling yard, receiving-and-departure yard), and intermediate ones are the elements of demurrage and waiting for operations at the basis and finite elements. Thus, the system in question can be seen as a series of phases, where any following phase is adjacent to the previous one, and each phase consists of a number of basis and intermediate elements. According to the order of servicing requests the same element of this system can be a part of several phases as their basis or intermediate element.

The state of an object under study at each time point T can be described by both input parameters A, which have ubiquitous character and are subject to certain regularities, and output parameters B, which value depends on the internal state S of the object during its maintenance at the basis and finite elements. Such a system can be represented as a simplified aggregate function:

$$\begin{cases} Z(T_b) = f(a_b, y_b, t) \\ Z(T_f) = f(a_f, y_b, t) \end{cases} \quad (4)$$

Considering the long demurrage of transportation flows at the intermediate elements of a marshalling yard, the ultimate state of this system is under serious adjustment:

$$\begin{cases} Z(T_b + \Delta) = f(a_b, y_b, t, \Delta t) \\ Z(T_f + \Delta) = f(a_f, y_b, t, \Delta t) \end{cases} \quad (5)$$

The impact of a parameter on the ultimate adequate behaviour of the system should be traced through a simulation model to show the impact of its elements within this parameter. The data obtained during simulation will determine the efficiency of operations at the marshalling yard and assess the reserves of its handling capacity [23]:

$$N_{my} = \sum_{i=1}^{N_f} \frac{T_i - t^z_{point.i}}{T^z_c(1+\rho)} K_{c.i} b_i \quad (6)$$

where Nf – number of freight zones; Ti – estimated time of an i-th freight zone work; $t^z_{point,i}$- time of non- freight operations; T^z_c- operation cycle of freight zones; $K_{c.i}$ - number of deliveries at the i-th freight zone within the T^z_c time; bi - average number of wagons within a delivery at the i-th freight zone; ρ – coefficient taking into account the occurrence of failures of mechanisation means at the i-th freight zone.

3 Results

The EuroSib-Novosibirsk Transport and Logistics Centre (TLC) is a part of the Eastern Transport and Logistics Zone of the Novosibirsk Transport Hub. The terminal is being developed as a backbone of a container train network connecting Siberian consignors and consumers with the ports of the Far East, North-West and distribution centres in Moscow. The Novosibirsk TLC's technological capacities today allow it to receive and handle two container trains per 24 hours. According to haulage statistics for 2017-2021, the average demurrage time of a local wagon fluctuates around 30 hours, which Figure 1 illustrates.

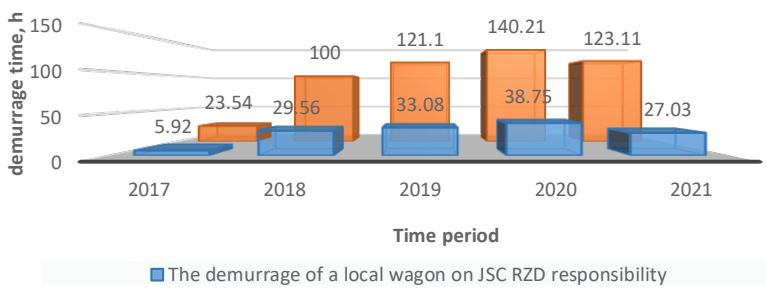
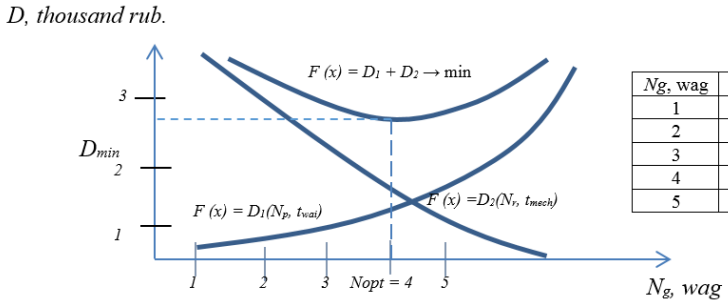


Fig. 1. Local wagon demurrage time rate at the Inya Vostochnaya marshalling yard of the West Siberian Railway, 2017-2021

A non-public railway track of JSC Express-Prigorod is taken to determine an optimal loading level for the loading-and-unloading zone. The results of modelling and finding the optimal loading level for the freight zone when handling wagons as part of two container trains are presented.

Means of mechanisation is a reach-stacker, C_{dem} w = 720 rub/wag per h, C_{dem} m = 960 rub/mech per h, N_{max} = 5 train, operating time of a freight point is 21 hours. Fig. 2 shows the result as graphs of cost dependence on the workload at freight zones.



N_g, wag	$D_1(N_p, t_{wai})$	$D_2(N_r, t_{mech})$
1	0.04	7.72
2	0.09	5.76
3	0.12	3.92
4	0.93	1.96
5	3.85	0

Fig. 2. Cost vs. workload graphs for freight zones

Thus, considering the minimum total cost of wagon and mechanism demurrage time, it is clear that the rational loading capacity for the loading-and-unloading zone is 4 container trains with the existing technology, technical equipment and performance indicators.

To prove these dependencies, a simulation model for the operation of an existing marshalling yard, Inya Vostochnaya in the West Siberian Railway, servicing several NPTs including Eurosib-N is developed as Figure 3 shows. As a result of simulation, the key operational indicators of the marshalling yard have been determined. From these results it is possible to compare several alternatives for the organisation of rail traffic between the marshalling yard and industrial facilities, and choose the optimal one in terms of functional reliability limitations for handling of wagons arriving into the transport system. Based on the results of multiple daily simulations, data on the change in the marshalling yard handling capacity by varying the parameters of marshalling yard operations were obtained. The behaviour of the system under study changes significantly when such values as the number of receiving-and-departure tracks, handling time at the receiving-and-departure yards, breaking-up time, number of locomotives, employment time of shunting locomotives (or their engagement), time for freight handling operations (loading-and-unloading time), time of making-up trains to departure and the working fleet of wagons are varied.

The simulation results for the analysis were averaged over 10 daily simulation experiments for each parameter under study. The maximum number of wagons in delivery on a non-public track is 45. Although queue lengths were not controlled in the model, delays in service occurred due to uneven engagement of marshalling yard facilities and loading-and-unloading points. Based on the developed model it is possible to determine the key indicators, such as the demurrage of wagons while waiting for their delivery and removal to the freight zone, locomotive engagement, exempt loading-and-unloading tracks, etc. and to optimise the operation of an enterprise by the results of simulated experiments. Table 1 presents the simulation results.

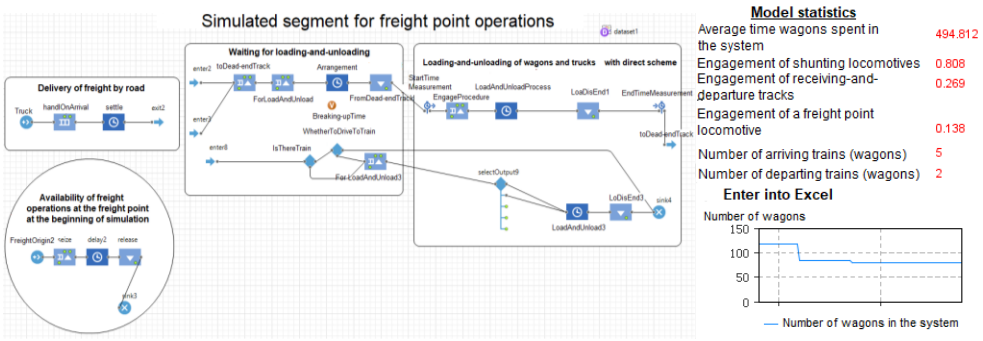


Fig. 3. A piece of the simulation model at work

Table 1. Simulation results by changing the parameters of the marshalling yard operation model

Parameter name		Parameter value	Average time wagons spent in the system, min		Engagement of shunting locomotives, %		Engagement of receiving-and-departure tracks		Engagement of freight point locomotives, %		Number of handled wagons, wag.	
Number of public tracks (PT)		3	777.3		83		79		32		45	
		4	716.2		83		69		31		45	
		5	677.2		92		44		36		150	
		6	677.4		92		37		37		150	
		7	676.9		91		32		36		150	
Handling time in the receiving yard, min		40	755.2		83		79		32		45	
		50	868.2		89		79		34		45	
		60	771.2		83		79		32		45	
		70	779.2		83		79		31		45	
		80	793.2		83		79		31		45	
Breaking-up, min	Breaking-up type	Back-in	Jolts	Back-in	Jolts	Back-in	Jolts	Back-in	Jolts	Back-in	Jolts	Back-in	Jolts
	Number of wagons in a cut	3	747.5	779.3	80	83	61	79	31	30	150	45
		5	775.3	773.3	80	82	79	79	30	30	45	45
		7	779.3	775.3	83	83	79	79	30	30	45	45
		10	777.25	771.3	83	83	79	79	30	30	45	45
		12	775.25	689.3	83	79	79	76	32	25	45	45
Number of locomotives, loc.		1	772.5		83		79		30		45	
		2	685.4		50		42		24		210	
		3	576.5		41		40		20		255	
Time for freight operations, min.		150	845.1		89		78		32		150	
		180	777.2		83		79		30		45	
		220	816.1		82		64		34		150	
		250	1039.2		91		77		35		45	
		360	1440.0		98		75		40		0	
Time for making-up trains to departure, min		50	811.2		87		79		30		45	
		80	837.2		87		79		31		45	
		110	867.2		89		79		30		45	
		150	911.2		90		79		30		45	
		170	927.2		90		79		30		45	
Number of wagons in delivery to the freight point, wag.		10	1085.2		98		81		52		45	
		15	1039.3		92		83		35		45	
		20	789.34		83		78		28		105	
		30	771.2		83		79		29		45	
		35	777.2		83		79		30		45	

Figure 4 shows the correlation dependencies of several parameters and reveals that the relation between the studied values is of non-linear nature. Thus, the behaviour of the transport system for maintenance a non-public track by the marshalling yard meets a random process in their mutual functioning, and the study of influence of local work individual indicators on the appropriate nature of the system's behaviour can be mathematically legitimate, but does not always truly reflect the real situational model. In this case, a typical feature of irreversible processes is that increasing the number of observations does not improve the model's characteristics, i.e. increasing the number of observations only worsens the predictive and analytical properties of the model.

The results of multiple experiments with the model show that, other things being equal, the number of shunting locomotives and receiving-and-departure tracks and their engagement during 24 hours as well as the size of the working wagon fleet have the most influence on the number of handled wagons, and the size of the latter determines the duration of freight operations at the optimal mechanisation load at simultaneous loading-and-unloading zones and the number of wagons in delivery.

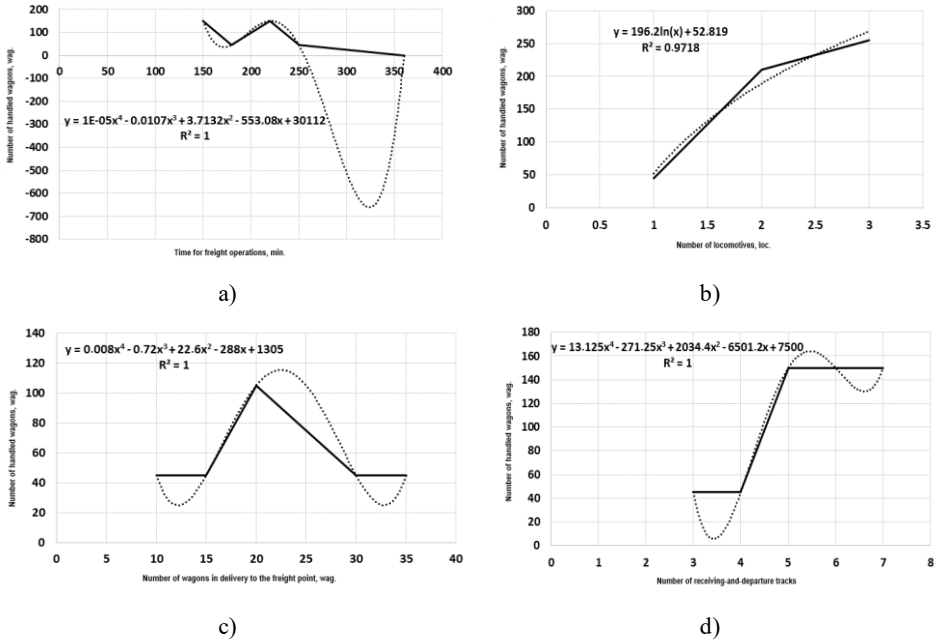


Fig. 4. Dependence of the number of wagons handled on: a) the time of freight operations with wagons; b) the number of shunting locomotives; c) the number of wagons in delivery; d) the number of receiving-and-dispatching tracks

Taking into account all the characteristics revealed, the value of handled wagon flow at the real NPT is determined. The actual daily schedule of the Inya Vostochnaya marshalling yard has been used for the analysis. Table 2 presents the NPTs serviced by the marshalling yard and the calculation parameters.

Table 2. Estimated data on NPT

Name of NPT	NPT of JSC “Je-P”	NPT of JSC "Krasnyj Jar tank farm"	NPT of T-4	NPT of LLC "Edinye Sistemy"	T MU	P NPT
Number of freight zones	1	1	1	3	1	2
Estimated time of work	20.33	20.92	20.83	19.08	20.3	18.9
Time of non-freight operations	18					
Operation cycle of freight zones	1.0	4.75	1.25	3.35	2.0	2.0
Number of delivery	2	1	2	5	1	3
Average number of wagons in delivery	10	32	8	35	16	6
Coefficient taking into account failures of mechanisation means	0,3					

The handling capacity of the marshalling yard will be:

$$N_{my} = \sum_{i=1}^{N_f} \frac{\mathrm{T}_i - t^z_{point.i}}{\mathrm{T}^z_c(1+\rho)} \mathrm{K}_{c.i} b_i$$
$$= \frac{20.33-18}{1(1+0.3)} 2 \cdot 10 + \frac{20.92-18}{4.75(1+0.3)} 1 \cdot 32 + + \frac{20.83-18}{1.25(1+0.3)} 2 \cdot 8$$
$$+ \frac{19.08-18}{3.35(1+0.3)} 5 \cdot 35 + \frac{20.3-18}{2(1+0.3)} 1 \cdot 16 + \frac{18.9-18}{2(1+0.3)} 3 \cdot 6$$
$$= 20.26 + 15.14 + 27.86 + 56.33 + 14.15 + 6.23$$
$$= 139.97 \text{ wag} \approx 140 \text{ wag}$$

The main result of this experiment is that having defined the key parameters ("number of receiving tracks at the marshalling yard", "train arrival interval" and "number of locomotives at the marshalling yard"), the possibility of 4 train dispatching was established with a shunting locomotive and receiving track engagement not exceeding 85 %, and a working wagon fleet not exceeding 140 wagons.

Certain technical and operational requirements must be met for these conditions, e.g. the number of receiving tracks as 6; the number of locomotives at the marshalling yard as 2; train arrival interval as 450 min.

Thus, using the real data of marshalling yard operations, one can carry out a design study of alternatives for the operating technology development and improvement, run a number of experiments by the model and draw expert opinions based on the analytical calculations made and the simulation results. The simulation model helps to make the most informed decisions on the construction of additional facilities at the marshalling yard, which will result in increasing the functional reliability of the marshalling yard, growing freight turnover and improving the quality of service for railway transport service users.

4 Conclusion

1. The developed methodology for running numerical experiments using the Marshalling Yard - NPT model takes into account the influence of the marshalling yard's wagon fleet on the volume of its handling, the engagement of shunting locomotives and the existing NPT maintenance technology (the sequence and order of servicing the arriving trains, the composition of deliveries to the loading-and-unloading tracks, the loading-and-unloading itself, etc.). It has been found that the volume of handling is broken at a certain size of the working fleet. This is due to the engagement of the marshalling yard's tracks with wagons, which limits its capacity in terms of composition of deliveries to loading-and-unloading points, as well as timely removal of already handled wagons.
2. The analysis of the results of experiments on the mutual influence of transport system reliability parameters makes it possible to determine that the number of shunting locomotives and receiving-and -departure tracks of the marshalling yard, their loading during a day and the working fleet size have the greatest influence on the amount of a wagon flow handled. Moreover, the duration of freight operations and optimum engagement of mechanisation means at freight points depend on the working fleet.
3. The model's performance is tested on a set of statistical data under the operating conditions of a real marshalling yard. The arrival of four trains allows the marshalling yard to operate normally; the maximum working wagon fleet is 140. If the number of incoming trains is increased, the train arrival interval is reduced, yet the technology remains unchanged, the marshalling yard will be paralysed due to the engagement of tracks and engagement of shunting locomotives. Thus, it is impossible to receive trains for breaking-up. The data from schedules of the simulation model of marshalling yard

operations and daily schedules show that with the increase in the number of trains under the existing operation technology, infrastructure availability and time for technological and freight operations the marshalling yard would not be able to serve the freight points on time and reliably.

References

1. P. Kozlov, et.al, Advances in Intelligent Systems and Computing **1116**, 1143-1151 (2020) https://doi.org/10.1007/978-3-030-37919-3_112
2. P. Kozlov, et.al, Advances in Intelligent Systems and Computing **1116,** 1064-1075 (2020) https://doi.org/10.1007/978-3-030-37919-3_104
3. Y. Timukhina, et.al, MATEC Web of Conferences **216,** 02025 (2018) https://doi.org/10.1051/matecconf/201821602025
4. S.A. Kosenko, A.A. Akimov, MATEC Web of Conferences **239**, 1–12 (2018) https://doi.org/10.1051/matecconf/201823905005
5. J. Kallrath, Optimization Letters **5,** 453–466 (2011) https://doi.org/10.1007/ s11590-011-0320-4
6. R. Loxton, et.al, Computers and Operations Research **39(12),** 3177–3184 (2012) https://doi.org/10.1016/j.cor.2012.04.004
7. H.D. Sherali, B.J. Lunday, Transportation Research Part E **47(2),** 263–283 (2011) https://doi.org/10.1016/j.tre.2010.09.005
8. M. Yaghini, Z. Khandaghabadi, Applied Mathematical Modelling **37(6),** 4127–7138 (2012) https://doi.org/10.1016/j.apm.2012.09.013
9. F. Olsson, European Journal of Operational Research **200,** 725–732 (2010) https://doi.org/10.1016/j.ejor.2009.01.024
10. M. Lawley, et.al, Transportation Research Part B **42(6),** 438–454 (2008) https://doi.org/10.1016/j.trb.2007.10.001
11. A.K. Narisetty, J.P. Richard, D. Ramcharan, D. Murphy, G. Minks, J. Fuller, Interfaces **38(2),** 89–102 (2008) https://doi.org/10.1287/inte.1070.0330
12. H.R. Sayarshad, T. Marler, Operational Research: An International Journal **10(2),** 175–198 (2010) https://doi.org/10.1007/s12351-009-0068-0
13. H.R. Sayarshad, et.al, Annals of Operations Research **181(1),** 185–197 (2010) https://doi.org/10.1007/s10479-010-0714-1
14. Y.-C. Lai, C.-S. Ip, Transp. Res. Part C Emerg. Technol. **79,** 18–41 (2017) https://doi.org/10.1016/j.trc.2017.03.006
15. L. Zhang, J. Transp. Res. Board. **2608(1),** 125–133 (2017) https://doi.org/10.3141/2608-14