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Application of Multicriteria Decision-Making Methods in Railway Engineering: A Case Study of Train Control Information Systems (TCIS)

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Additional information is available at the end of the chapter

Abstract

In order to improve its position in the transport market railway, as a complex system, it has to fulfill a number of objectives such as increased capacity and asset utilization, improved reliability and safety, higher customer service levels, better energy efficiency and fewer emissions, along with increased economic viability and profits. Some of these objectives call for the implementation of maximum values, while some of them require minimum values. Additionally, some can be expressed quantitatively, while some, for example, customer service, can be described qualitatively through a descriptive scale of points. The application of MCDM in railway engineering can play a significant role. Therefore, the major objective of this chapter is the review of the application of MCDM methods in railway engineering. As one of the means in achieving the objectives of railways and above all the utilization of capacity are Train Control Information Systems (TCIS). Based on that, the aim of this chapter is the evaluation of the efficiency of TCIS in the improvement of railway capacity utilization through defined technical-technological indicators. The non-radial Data Envelopment Analysis (DEA) model for the evaluation of TCIS efficiency in improvement of utilization of railway capacity using the selected indicators is proposed. The proposed non-radial DEA model for TCIS efficiency evaluation in using railway capacity could be applied to an overall network or for separate parts of railway lines.

Keywords: evaluation, efficiency, railway, capacity, train control information system, non-radial DEA model

1. Introduction

1.1. Background

Transport activity in the European Union (EU) is expected to continue growing but with slower trends than in the past [1]. From 1995 to 2012, freight transport in the EU28 countries showed an overall growth of 22.8%, while passenger activity was slower with 19% [2]. According to the [1], the increment of freight transport activity is expected to be 35% from 2010 to 2030 and 58% from 2010 to 2050, while passenger activity growth will be slightly lower at 22% until 2030 and 40% until 2050. Railway as a backbone of the EU transport system has the potential to play a key role in addressing rising traffic demand, congestion, fuel security and decarbonisation, but many European rail markets are still facing stagnation or decline [1].

The demand for railway transportation is steadily increasing around the world [3]. Regarding the EU, railway transport activity is expected to grow in terms of passenger transport by 39% between 2010 and 2030 and 76% from 2010 to 2050, as well as freight transport by 47% by 2030 and 84% during 2010–2050. Therefore, railway share of the transport market related to passenger transport will be increased to 1 percentage point by 2030 and an additional percentage point by 2050. Similar increases in modal share for passenger rail are expected for freight transport [1].

However, because the many railways use capacity close to maximum, it is necessary to take adequate actions in order to meet the new demand. Accordingly, possible actions could be building a new railway infrastructure, upgrading existing infrastructure or using the existing infrastructure more efficiently [3]. Consequently, the main challenge of many railways around the world is limited availability of capacity for all trains of their infrastructure related to topological configuration; although in some cases the capacity of infrastructure was not changed despite doubling, tripling or quadrupling tracks.

Railway capacity may be defined in different ways [3]. Indeed, in the railway market and in the literature, there are numerous definitions and meanings of railway capacity [4, 5]. Railway capacity is seen as a simple but rather inaccessible concept. Although unique, a true definition of capacity is impossible, because capacity depends on the way it is utilized. An overview of some important definitions of railway capacity was presented in [6]. One of the most appropriate definitions of railway capacity for this chapter was declaimed by [4]. They stated that railway "capacity is a measure of the ability to move a specific amount of traffic over a defined rail line with a given set of resources under a specific service plan."

In order to tackle the railway capacity challenge, since the building of new railway lines is extremely costly and time-consuming, efficient utilization of railway infrastructure is essential. Therefore, there is a need for better planning and efficient management of measuring used capacity, as well as better enhancement measures [6]. Analysis and evaluation of railway capacity is a multifaceted and complex task because it involves several

complex systems, such as railway infrastructure, rolling stock, timetable and human behavior, and some other influencing factors such as the number of tracks connecting the stations, station track layout, the signaling system, train performance, speed difference between train services, market demand, reliability and delay acceptance of railway customers.

As a multidisciplinary area different factors impinge, such as timetable, signaling, nodal capacity constraints, rolling stock, infrastructure, external factors and governance impact on railway capacity utilization. Signaling as a kind of traffic management systems (TMS) and one of the classes of train control information systems (TCIS) ensures the safe running of trains within the infrastructure. With advanced signaling systems, such as European Railway Traffic Management System (ERTMS), besides the improvement level of safety, reduction of headway and blocking time of infrastructure may be achieved [6, 7].

According to [7], TCIS represent a complex system composed of a large number of various kinds of components (mechanical, electrical, computer, etc.) with different types of interactions (local, simultaneous, etc.), which are interconnected and operate in synergy with each other. In their chapter, TCIS are grouped in four classes where each class includes subsystems, that is, Interlocking Systems (IXL) including subsystems such as train detection equipment (track circuits or axle counters), switching points and level crossings; Traffic Management Systems (TMS) that imply ERTMS, Positive Train Control System (PTCS), Chinese Train Control System (CTCS) and Railway Signaling System (RSS); Automatic Train Control (ATC) systems including Automatic Train Protection (ATP), Automatic Train Operation (ATO) and Automatic Train Supervision (ATS) subsystems; and In-Cab Train Advisory (In-CTA) systems which include the In-Cab Information Support System and the Driver Advisory System (DAS). Based on that and the fact that signaling is only a part of TCIS, that is, it represents a kind of TMS in the evaluation just of its impact on railway capacity utilization is not enough. Therefore, in this chapter the evaluation of influence of comprehensive TCIS, as a system composed of various subsystems, on railway capacity utilization is considered.

1.2. Aim and scope of the chapter

Since railway capacity utilization is a multidisciplinary area that depends on different factors, in this chapter applications of MCDM methods for the evaluation of the influence of TCIS on capacity utilization are considered. Based on the fact that signaling as a part of TCIS contributes to efficient railway utilization, the main aim of the chapter is to propose a new approach for evaluation, monitoring and comparison of efficiency of TCIS on both macro and micro levels for improving railway capacity utilization.

The key objective of the chapter is the introduction of the non-radial DEA model for the evaluation of the efficiency of TCIS influence on the improvement of railway capacity utilization. Through the literature review related to evaluation and analysis of railway capacity utilization, application of non-radial DEA model in evaluation of efficiency of TCIS influence on

capacity utilization with some real and some assumed data (these were necessary because of the unavailability of the real data and information), only for Serbia and Austria case studies was conducted.

A literature review related to railway capacity analyzing provides confirmation of the novelty of the application of the non-radial DEA model for the efficiency evaluation of TCIS in the improvement of railway capacity utilization and guidelines for selection of desirable and undesirable inputs and outputs for the application of the non-radial DEA model. Also, through application of the non-radial DEA model, sensitivity analysis was presented.

Within the next section, the literature review related to analysis, measurement, evaluation and improvement of railway capacity utilization, followed by an overview of factors and parameters that influence capacity consumption, as well as previous considerations of impacts of TCIS or only signaling systems on capacity utilization are presented. Section 3 contains the history of TCIS and case studies used for the evaluation. Introduction of the DEA method in efficiency evaluation of TCIS on railway capacity utilization with selection of DMUs, inputs and outputs as well as the results of DEA method application are presented in Section 4. Section 5 discusses the application of the MCDM in other areas of railway engineering. Finally, in Section 6 conclusions and proposals for future work are summarized.

2. Literature review

Railway capacity represents an interesting topic and is extensively discussed in the literature by scholars [8]. For railway capacity improvement, two basic approaches are followed: upgrading or expanding the infrastructure, and improving operational characteristics and parameters of the extant rail services. With each approach, it is necessary to assess and analyze the benefits, limitations and challenges through capacity analysis.

There are different capacity analysis approaches and methodologies where input typically includes infrastructure and rolling stock data, operating rules and signaling features [9]. In the following subsections, major comprehensive studies that deal with measuring, analyzing and improving, as well as defining and classifying the capacity utilization, are presented.

2.1. Methods, techniques and approaches in the evaluation of capacity utilization

In the literature, there exist different methods for estimation of utilization of railway capacity and different categorizations of these methods [6]. For example, capacity methodologies have been divided into two major classes as analytical and simulation [10]. Also, capacity methods were categorized to timetable-based and non-timetable-based approaches [11].

Overall, the analytical and simulation methods are the most common methods found in the literature, while one example of combined approach was presented in [12].

A review of the main concepts, methods and techniques of assessing railway capacity was presented in [4, 8, 13], as well as the main factors that can affect railway capacity were also

analyzed in [4]. A detailed review of all of these methods, approaches to defining and analyzing and factors affecting the railway capacity may be found in [6].

With these methods in the literature, theoretical, practical capacity as well as used capacity and available capacity were considered [3, 13].

2.1.1. Analytical methods

Analytic capacity determination models were developed by [14]. In addition, in [15] also a number of approaches for determining the capacity of railway lines and associated factors in railway operations were discussed. Some of the analytical approaches used in the evaluation of railway capacity for determining absolute capacity could be seen in [16] and others that estimate secondary delays due to route conflicts and train connections in [17]. In [18], an analytical queuing-based approach was proposed while authors of [19] proposed an analytic model. Consideration of capacity evaluation based on the UIC capacity leaflet which is most often used by European railways was presented in [20].

In the UIC code 406 [21], a methodology for capacity evaluation is developed while the applicability of UIC 406 code as a timetable compression technique for evaluation of the corridor and station capacity was considered by [22]. Based on the approach used in the highway capacity manual to analyze capacity of road traffic in [23], a model for railway capacity was developed. Based on that in [24], the headway-based models were further developed.

In [5], an analytical method that is used in Lithuania for calculation of railroad line capacity, *metro-train* method and *UIC 406* method was presented. According to [9], the UIC method is also one of the major tools for improving capacity utilization, whereas in Britain, authors of [25] pointed out Capacity Utilization Index (CUI) also is effective.

Authors of [25] further described the extension of existing capacity utilization measures to enable their application to both junction and station nodes.

A new model for capacity consumption calculation, similar to the UIC 406 method, was presented by [26]. Using the UIC 406 method, [27] calculated the capacity utilization of the Zagreb-Rijeka railway line and sections. Expansion and improvement of the UIC 406 method was made by [28].

2.1.2. Optimization methods

Application of an optimization method in analyzing the capacity of new corridors and considering uncertainty of demand levels on the planned route was conducted by [29]. A new method to optimize the travel speed of trains was presented in [30]. Then, in [4] a tool for railway managers called Modulo Optimizador de Mallas (MOM) was developed.

Using an optimization approach in [31], the capacity consumption for railway routes under construction was calculated. [32] presented an integer-programming model for both line and line section for evaluation of train type interactions on railway line capacity. In [33], an optimization approach for analyzing the Beijing-Shanghai high-speed railway line was developed.

An overview of the optimization models used to decide when a fix budget is given and where track duplications and subdivisions should be made has been presented by [34]. In order to solve the station carrying capacity problem with an integer linear programming model was created in [35], while mechanism for optimization of capacity of the main corridor within a railway was developed in [36], while in [37] an optimization algorithm RECIFE-SAT suitable for quantification of capacity by solving the saturation problem adding as many trains as possible to an existing (possibly empty) timetable was proposed.

2.1.3. Simulation methods

Simulation methods use general simulation tools, such as AweSim, Minitab and Arena or commercial simulation software specifically designed for rail transportation, such as RTC, MultiRail, RAILSIM, OpenTrack, RailSys and CMS [9]. In [38], Strategic Capacity Analysis for Network (SCAN), developed by [39], was discussed.

A microscopic simulation method for analyzing capacity of a station and complex railway nodes has been introduced by [40, 41], respectively.

In order to analyze railway capacity, Lindfeldt [3] employed several different methodologies.

2.1.4. Parametric models

In order to describe and analyze railway capacity, parametric models use some parameters of railway infrastructure. [42] has introduced an enhanced technique of capacity evaluation tools. Parametric models were also developed by [43] for evaluating the capacity of single- and double-track operations using the microscopic simulation software Rail Traffic Controller (RTC). Using RTC, in [44], the simultaneous operations of passenger and freight trains in single- and double-track configurations were compared. Parametric capacity analysis and simulation as two common capacity evaluation methods were described by [45].

2.2. Consideration of influence of TCIS on capacity consumption

Regarding the TCIS and capacity utilization, in [46], a thesis in terms of consideration of capacity increment crossing with the fixed block to the moving-block operation (ERTMS level 3) was presented. In [47], several different methods of capacity evaluation to investigate the effect of different signaling systems on the capacity of a double-track bottleneck in Stockholm were used.

Because advanced signaling systems have recently been considered as a potential solution for increasing system capacity, regardless of the fact that they usually require a great amount of capital investment, the Taiwan Railways Administration (TRA) was interested in estimating the possible capacity benefits of adopting these new signaling systems.

An assessment of maximum capacity at 360 kph (225 mph) based on current technical capability and potential improvements in the capability, were presented by [48].

In order to understand the potential benefits of adopting various advanced signaling systems, such as hybrid or moving-block systems, in [49] a set of analytical capacity models for

conventional rail operations with advanced signaling systems, which were implemented in the busiest corridor in the Taiwan Railways Administration system, were developed.

In [50] a new concept of dynamic infrastructure occupation to assess infrastructure capacity was proposed. A new concept was applied in a capacity assessment study of a Dutch railway corridor with different signaling configurations under both scheduled and disturbed traffic conditions. Within their study, comparison of the two different signaling systems, Dutch NS'54/ATB and ETCS Level 2, and their influence on capacity was conducted.

Based on the proposed assessment of the daily capacity improvements deriving from the application of the ETCS signaling system, [51] compared capacity in terms of maximum number of daily trains, between the base Telephone Block system, the ETCS level 2 scenarios and ETCS level 3 with moving block. Using blocking time model, [52] presented headway of signaling systems and headway between trains that are running under different signaling systems. Also, using the simulation software RailSys, they analyzed the effect on capacity when trains are in different signaling systems such as moving block, fixed block and their mix sharing a line of Beijing metro.

In terms of signaling system and capacity, in [53] a design approach able to identify the signaling layout which minimizes the investment and maintenance costs, while respecting the required level of capacity was presented. With increasing the levels of automation within a railway in [54] provided the preliminary hypothesis and methodology for testing them in terms of the capacity increase that comes with them. They concluded that the reliability of a railway network would improve with increasing levels of automation.

2.3. Review of important influence factors and parameters of railway capacity

Since the purpose of this chapter is the evaluation of the influence of TCIS on railway capacity utilization on the macro level, one of the steps of the chapter is presentation of interactions of TCIS with capacity utilization through an adequate set of variables rather than a detailed technical description of different TCIS. Therefore, as a starting point of introducing MCDM methods for evaluation of TCIS in terms of capacity utilization the identification of factors and parameters which affect railway capacity utilization is necessary.

The railway capacity is not static but depends on the infrastructure, operating conditions [4] and overall elements that make up the railway system [55]. As already pointed out, railway capacity is a multidisciplinary area, so different factors affect its utilization [6]. The fundamental factors that affect railway capacity and should be considered in its evaluation, according to [4, 55] are grouped as infrastructure, traffic and operational parameters [4, 55].

Among the infrastructure parameters we can include:

1. *The signaling system* combined with the track layout can be crucial for capacity [3]. A *block section* is a section of track that can only be occupied by one train at a time. *Block section length* is an important factor because together with the spatial distance between two following trains it determines the maximum traffic intensity. For a conventional signaling system with fixed block sections, the length of the block sections on the line is important

for the minimum headway between two consecutive trains in the same direction [3]. Besides the block and signaling systems also, train speed and train length are important infrastructure factors.

2. The important factor for capacity is the *number of tracks on the line*, that is, *single/double or quadruple tracks* [3]. Lindfeldt [3] also pointed out that the capacity of a double track is four times that of a single track, and a quadruple track three times that of a double track. This is possible due to meeting trains everywhere on the line without being restricted to the crossing stations; while on quadruple tracks, trains going in the same direction can preferably be separated according to mean speed. Many until now proposed methodologies only addressed the case of single-track lines with its extension on double-track lines. However, on double-track lines consideration should be separately made for the trains of both directions [55].

3. *The definition of lines and routes* that includes a list of stations and halts along the line and their characteristics is also important because the capacities of railway lines and nodes are key issues in consideration of overall railway capacity [55].

4. *Network effects* that consider what happens on the interfering lines; *track structure and speed limits* that include conditions of the rails, ties and ballast dictate the weight and type of equipment that can be used on the line, as well as the speeds allowed on the line.

    Speed is especially important for single-track lines, where higher average speed means that crossings can occur closer in time, while on double-track lines speed does not have as big an impact on capacity as on single-track lines and has a similar effect for the frequency of overtaking as for crossings on the single-track line. For higher speed in the case that the signaling is based on fixed signal block sections block sections are cleared faster, while the effect is neutralized by trains with higher speed due to longer breaking distance [3].

5. *Length of the subdivision* is lengths of line sections between stations plays important role for railway capacity.

Regarding the traffic parameters the most important factors that should be considered are *new or existing lines*; *traffic mix* in terms of types of trains and their speeds; *regular timetables*; *traffic peaking factor*; and *priority* of trains.

Track interruptions; *train stop time*; *maximum trip time threshold*; *time window* and *quality of service, reliability or robustness* represent the most important operational parameters.

One of the important factors for understanding how modern signaling affects and can improve capacity utilization is *blocking time* defined as "the time interval in which a section of track is exclusively allocated to a train and therefore blocked for other trains" [6]. Authors of [27] pointed out that capacity of railway lines depends on the *minimum headway time* of the trains, which is related to the structure of the signaling system; and differences in headway time are the result of changes in travel speed.

According to [8], in the paper [16] it was shown that the capacity of the railway network is affected by factors such as *train speed*, *train heterogeneity*, *distance*, *sectional running times*, and *directional and proportional distribution of trains*.

In [42], they classified *length of subdivision*, *siding length and spacing*, *intermediate signal spacing*, *percentage of number of tracks*, that is, *single, double and multi-tracks*, *heterogeneity in trains* in terms of train length and power-to-weight ratios among infrastructure and operational factors that influence the railway capacity levels. As key factors that have a direct impact to railway capacity, in [13, 56] *geometrical configuration of the track*, *line* and *stations* and *layout*, *features of signaling systems*, *movement rules* and corresponding *minimum distance between trains*, operation and maintenance planning were pointed out. The main parameters that affect determination of capacity within the infrastructure parameters are *number of tracks*, *distance between two crossings* or *passing stations*, *total reference time*, *theoretical speed* and *project speed*, while operational parameters include *rolling stock features*, *traffic typology* and *headway* [13].

Among operational effects, parameters that have been included by [13] are generation and propagation of *delays*, as well as required and expected *quality of service*. In order to describe factors that affect railway capacity, used capacity and symptoms of high capacity utilization, in [3] performance indicators based on the available data were selected. Presented indicators for capacity are related to infrastructure, traffic, timetable and delay indicators.

For infrastructure indicators such as *distance between crossing stations (km)* for *single track and distance between passing stations (km)* and *all lines and stations (m)* for *double track* were selected. Within the timetable indicators *number of trains per day* (*total/passenger/freight*), *number of trains per hour* (*total/passenger/freight*), *speed (km/h)* (*passenger/freight*) and *speed difference* were selected. In terms of traffic indicators *weight (metric tons)*, *length (m)*, *number of axles* and *axle load* were chosen for freight trains and *gross tons/day (metric tons)* for passenger trains. For passenger/freight, *proportion of trains with increased delay*, *median of increased delay normalized by route distance [min/100 km]* and *standard deviation of increased delay normalized by route distance [min/100 km]* were placed as delay indicators.

In the model developed in [43], factors used for single-track operation are *siding spacing*, *signal spacing*, *track speed*, *volume (trains/day)* and *heterogeneity*. For double-track, the factors are *crossover spacing*, signal spacing track speed, *volume* and *heterogeneity*. In evaluation capacity of single and double tracks in [44], key factors such as *traffic volume*, defined as *the total number of trains per day (TPD)*, *traffic mixture (heterogeneity)* as the percentage of these that are freight trains and describes the train type heterogeneity of the corridor, *the maximum speed* of the passenger train and the *number of main tracks on the line* were used.

In the literature, the main metrics of capacity level measurements have been categorized through three groups [9]. Within the first group, - i.e., throughput - were categorized *number of trains*, *tons*, *train-miles*. *Terminal/station dwell*, *punctuality/reliability factor*, and *delay* represent metrics of the second group level of service, and asset utilization, the third group, includes *velocity*, and *infrastructure occupation time* or *percentage*. [9] also emphasized that the Federal Railroad Administration (FRA) introduced a parametric approach developed to measure capacity in the U.S. rail network based on *delay units* (*hours per 100 train-miles*), while European operators use throughput metrics (*number of trains per day or hours*), where punctuality and asset utilization metrics are also applied as secondary units.

In [9] also characteristics that have impact on capacity and its utilization and categorized them into infrastructure, signaling, operational and rolling stock characteristics were reviewed.

However, there is a dilemma as to how these characteristics and their differences were considered in various capacity analysis tools and methodologies.

As demonstrated in literature, the railway capacity rate is controlled by some major components, however in this chapter not all these aspects are taken in account. According to the objective of the chapter, the attention is focused on the evaluation and comparison of the impact of TCIS on capacity utilization deriving from a different TCIS and parameters related to it rather than the other components previously listed.

3. History of the development of railway signaling systems

From 1850, the moving of trains from one to another block was regulated by train dispatchers standing at blocks along the line with a stopwatch. They used hand signals to inform train drivers that a train was going to pass. By 1900, mechanical semaphores were introduced and with the innovation of the telegraph and telephone, the staff was able to send a message (first a certain number of rings on a bell, then a telephone call) to confirm that a train had passed and that a specific block section was finally clear [57].

In 1930, the first optical signals were introduced and the whole system was called *phone block system* [57]. During the middle of the twentieth century, many railways adopted fixed signals. Early fixed signals were semaphores which later on were replaced by traffic light signals with two aspects (green and red), three aspects (green, yellow and red or double green, green and red) or four aspects (green, double yellow, yellow and red) that provided necessary information to the train drivers [6].

3.1. Introduction of the semiautomatic and automatic block systems

The *semiautomatic block* was introduced when fixed signals had replaced hand signals. However, today railways are equipped with signaling systems based on the automatic blocks which do not require manual intervention. With automatic blocks (interlocking), the rail line is divided into blocks of which the length should be longer than the braking distance of the faster train running on the route, and where the occupancy of the blocks is detecting with the train detection equipment (track circuit and axle counter). In the early 1980s, railway signaling systems were upgraded in order to be able to constantly monitor the speed of the train and improve safety, through automatic braking if the driver fails to respond to the warnings such as a train passing a red (danger) signal or exceeding a speed restriction – these are known as Automatic Train Protection (ATP) systems [57]. Each country has its ATP, and there are now 20 different developed and operated ATP systems in the EU [58] according to the different national requirements, technical standards and operating rules [57].

3.2. Development of standard European signaling system

In order to remove more than 20 different TCISs across the European railway network [58], the EC decided to support the implementation of a harmonized standard for the railway

control and signaling systems, the European Railway Traffic Management System (ERTMS) [59]. The ERTMS as a kind of Traffic Management System (TMS) is one of the classes of TCISs along with the Interlocking Systems (IXL), Automatic Train Control (ATC) systems and Automatic Train Supervision (ATS) systems [7]. The study [7] gives detailed classification of TCISs classes. ERTMS as a standard Automatic Train Protection (ATP) and Automatic Train Control (ATC) are complementary systems that ensure safer operation of trains and can enhance capacity utilization [6].

Besides standardization, ERTMS was created to providing interoperability for different countries and manufacturers leading an increase in the efficiency of traffic of both passenger and freight trains and the competitiveness of the European railway [60]. The realization of interoperability is a precondition for other benefits of ERTMS, such as improved traffic management, optimized usage of energy and network resource [61], enhanced profitability and customer service, with a contribution to overall environmental and energy efficiency objectives [62]. In addition, higher levels of safety for high-speed trains with only a few minutes headway between trains ensures operational reliability and more traffic within the same infrastructure, that is, better capacity utilization, reduction of maintenance costs [60, 63, 64] as well as the creation of a common market of signaling equipment that also leads to reduction of costs [62–64].

3.2.1. Description levels of ERTMS

ERTMS consists of three levels. Level 1 represents track to train communication, provided by Eurobalises located along tracks that interface with the existing signaling system and line-side signals. It is based on 'fixed block' and fixed braking distance. However, the lower deceleration rate in ERTMS level 1 results in lower capacity utilization.

Level 2 is an enhancement of Level 1 with movement authority from Radio Block Centre (RBC) through interlocking to on-board ECTS via GSM-R link, which enables the elimination of trackside signals. Level 2 covers track-to-train communication and vice versa. On this level, RBC calculates the correct movement authority, giving authorization to proceed (or not), with balises used to transmit static messages such as location, line profile and speed limit. This level enables higher operational speeds and reduced headways, thus more efficient capacity utilization because it is also based on a 'fixed block system' though it eliminates the time needed for the driver to see the trackside signals as there is cab signaling which is displayed on-board.

Level 3 improves the ability of Level 2 so that train detection by the trackside is no longer required. At this level, the RBC uses GSM-R for transmission between track and train. Compared with Level 1 and 2 that are based on a fixed block signaling system, Level 3 allows a moving-block signaling system; this means that as the train travels, the track receives the train location and train integrity from the train. Levels 1 and 2 are already widely applied in Europe, while Level 3 is currently under development [6]. Therefore, in modern signaling, like an ERTMS Level 3, line-side signals are not required as the necessary information is displayed in the driver's cabin and intends to introduce moving blocks which can further decrease headways [6]. With ERTMS level 3, the time needed for the driver to see the trackside signal because of cab signaling (because moving blocks are dynamic and can be much shorter than fixed blocks) is eliminated. Hence, with European Cab-based signaling (ERTMS)

improvement of the capacity utilization can be significantly achieved by more efficient train control and higher speed while safety can be also increased through reducing the safety distance, that is, shorter blocks between trains and decreasing headways so the time of the occupied block results in faster journeys [6].

3.3. Case studies of TCIS evaluation

Within the EU each country has its own TCIS. For introduction of MCDM in evaluation of the influence of TCIS on capacity utilization based on the available data and information used for assumption of data only two case studies, that is, Serbia and Austria were considered.

3.3.1. Austria case study

Austrian TCIS: The almost comprehensive Austrian railway network has a computerized train monitoring system. The train radio system was upgraded to European GSM-R standard by infrastructure managers of the Austrian railway network. Further, the Austrian railway network is equipped with the "Punktformige Zugbeeinflussung" system (intermittent automatic train running control system, PZB), which is the descendant of the "Linienzugbeeinflussung" system (continuous train protection, LZB) and provided warnings and enforced train braking.

Also, on some rail sections LZB and ETCS systems are in use. Newly constructed lines "Wienerwaldtunnel" (Abzweigung Knoten Hadersdorf – Tullnerfeld – Knoten Wagram) and "Unterinntal" (Kundl – Radfeld – Abzw. Baumkirchen), planned to be equipped with a reduced level of signaling, can be used exclusively by trains equipped with the Level 2 ETCS, while all other lines equipped with Level 1 ETCS can also be used by the PZB system.

On the Austrian network, ETCS Level 1 system was installed on five rail sections of total length 381 km, while ETCS Level 2 system also in five rail sectors of total length of 447.4 km. Several plans exist for investments concerning the installation of ETCS Level 1 and 2 systems which are expected to be ready through a time period from 2012 to 2025 [65].

3.3.2. Serbian case study

Serbian TCIS: On the Serbian railway network TCIS differ from one railway line to the other. Along the railway line Belgrade – Novi Sad – Subotica a copper signal/telecommunication cable is used and on this railway section an automatic railway network is in function. The telecommunication equipment installed is at very low level, while the electrical system was brought to its limit for the railway line Belgrade-border Croatia.

Along the railway line Belgrade – Niš and in specific sectors, an STA signal – telecommunication coaxial copper cable is in use. On the railway line Niš – Preševo, a signal – telecommunication copper STA cable is in use and the line is covered by a radio dispatch system for direct communication between the telecommand center in Niš and trains in operation.

The telephone switching system operates by means of switching nodes of outdated technology based on space division multiplexing. On these two lines, the railway telephony system

and dispatch links were realized in relay technology from the 1940s. Along the railway line Niš-border of Bulgaria, there are trackside telecommunication devices and aerial telephone cables installed and used. In Dimitrovgrad, there is an automatic railway operation network terminal (so-called ŽAT) center which is connected to an existing nodal ŽAT center in Niš. None of these systems support the installation of modern digital signaling devices, systems for traffic control and information technologies. Based on this, it is clear that the Serbian railway network is equipped with outdated telecommunication systems.

On the Serbian network, there is no automatic traffic control, but an intermittent inductive automatic train stopping device for the control of the trains, including the stationary part close to the track, transmission system and locomotive part. Regarding the ETCS/ERTMS at Serbian railway along the lines of Corridor X are planned to be installed [65].

4. Methodology of the TCIS evaluation with non-radial DEA model

Within the first step of this chapter, the non-radial DEA model was introduced. After that for the purpose of evaluation of TCIS inputs and outputs for the introduced model (M) were defined and then these inputs and outputs were classified as desirable and undesirable. Since the overall real data is missing, application of the non-radial DEA model was tested mainly on the assumed data. This step was followed by a selection of DMUs for evaluation of TCIS, that is, years of TCIS functioning for case studies, and based on the availability, data for them were collected. In the fourth step, the selection of weights for desirable and undesirable inputs and outputs was performed. Finally, the validation of the model (M) through perturbation of the used data was presented in order to check the behavior of the model. In the following subsections, the detailed description of all steps are given.

4.1. Introduction of DEA method in the evaluation of efficiency of TCIS on railway capacity utilization

As the objective of this chapter is to determine the efficiency of TCIS and the monitoring of its effects on railway capacity utilization, there is a need to provide a potential tool for monitoring, evaluating and benchmarking changes of TCIS impacts on the consumption of railway capacity. In this study, the Data Envelopment Analysis (DEA) methodology, as a good tool for measuring the efficiency and impacts of TCIS in terms of efficiency of using railway capacity at different levels, was considered.

DEA can be used for tactical and strategic planning especially where managerial comparisons between the relative efficiency of some units (e.g., railways of different countries, train-operating companies, stations, etc.) [66]. The DEA is a well-known "non-parametric productive efficiency measurement method for operations with multiple inputs and multiple outputs" [67].

The DEA method, first popularized by [68], combines and transfers multiple inputs and outputs into a single efficiency index, forming the "efficient frontier" with a set of Decision-Making Units (DMUs) pointing toward best practices and assigning a level of efficiency to other DMUs that are not on the frontier according to the distance to the efficient frontier [67].

Today, there are different DEA models for measuring efficiency for different types of measuring requirements [67]; among them, according to [69], the most well-known are the CCR model [68], the BCC model [70], the Additive model [71] and the Cone Ratio model [72]. Within these DEA models, only desirable inputs and outputs are considered, without consideration of undesirable inputs and outputs which can appear in real applications. For example, in evaluating the efficiency of TCIS on railway capacity, different factors can be modeled as undesirable. Therefore, in this study, non-radial DEA model which modeled some inputs and outputs as undesirable were introduced and considered.

DEA has been used by economist in the field of railways in order to analyze economic efficiency. However, it was also applied to railway capacity and provided promising results on improvement of the capacity utilization at railway stations and passenger train operators in the United Kingdom [66].

For the measuring of efficiency related to the contribution of TCIS on better utilization of railway capacity on the macro level, non-radial DEA model (M) that includes both desirable and undesirable inputs and outputs was employed. Based on the data for Serbia and Austria, the non-radial DEA model (M) was piloted for evaluation of efficiency of TCIS contribution to railway capacity. In the investigation of the non-radial DEA model (M), factors that affect the railway capacity utilization and are related to the TCIS were considered as guidelines in the selection of inputs and outputs. Besides the other widely used non-radial DEA models such as Slack-based models, Russell measure models and Directional distance function, in this chapter non-radial DEA model (M) was chosen due to its ability to employ different non-proportional adjustments, decision-maker specified weights assigned to each efficiency score, and because of its ability to proportionally decrease the amounts of energy inputs and undesirable outputs simultaneously as much as possible [73, 74].

Based on the results obtained by applied data and sensitivity analysis, it could be said that the proposed non-radial DEA model (M) could be applicable for providing information about the role and efficiency of TCIS on using railway capacity for various levels. Moreover, it could be used as a support tool for identifying the best practices in terms of the type of TCIS, factors that cause better or worse roles of TCIS related to use of railway capacity, as well as testing and monitoring the role of TCIS in different railway capacities such as theoretical and practical.

4.2. In brief about DEA model

DEA is a linear programming method for efficiency measurement based on Farrell's original work [75] that was later popularized by authors of [68]. DEA has been commonly applied in empirical literature as a non-parametric frontier approach for evaluating the relative efficiency of a comparable set of entities, called DMUs, with multiple inputs and outputs, that is, DMUs that are able to transform multiple inputs into multiple outputs. This method offers decision-makers (DMs) information on efficient (i.e., best practice) and non-efficient DMUs. A major stated advantage of the DEA is that it does not require any prior assumptions on underlying functional relationships between inputs and outputs [76]. Additionally, the method does not require prior definition of weights of criteria for input and output by DMs, as all weights

are determined after solving the DEA model, which eliminates subjective decision-making. Assuming that there are n DMUs, m outputs and s inputs, efficiency score is usually calculated based on the input-oriented Charnes, Cooper and Rhodes (CCR) DEA model [76, 77] that can be written as: $\min \theta; s.t \, X\lambda \leq \theta x_i, Y\lambda \geq y_i, \lambda \geq 0$,

where X, Y and x_i, y_i are data matrices and vectors of inputs and outputs, respectively, λ is a vector of variables. θ represents an indicator of technical efficiency, where $\theta \in [0, 1]$ and indicates how much an evaluated entity could potentially reduce its input vector while holding the output constant. The presented CCR model exhibits the constant returns to scale (CSR), but with the additional constraint $\sum \lambda = 1$, CCR model becomes the classical Banker, Chames and Cooper (BCC) model that allows the variant to return to scale (VRS) [70, 76].

4.3. Description of non-radial DEA model

The classical DEA model is strongly related to, and can be presented through, production theory, where raw materials and resources are treated as inputs, while products are treated as outputs in the production process. However, in some real applications, production process may also use undesirable inputs and generate undesirable outputs [69], like smoke pollution or waste [78, 79]. Consequently, authors of [80, 81] have stated that in that production process both desirable and undesirable factors may be presented within the models of DEA methodology.

DEA models with undesirable inputs and outputs have been extensively studied [69]. Some of these papers are summarized below. For instance, in [81] an alternative approach to treating both desirable and undesirable factors differently in the BCC model was developed. In [82], the control of changes in input/output levels of a given DMU with the presence of undesirable factors in order to preserve the efficiency index of a DMU was considered. In [79], a model in the framework of DEA for treating undesirable inputs and outputs was proposed. A method for treating both undesirable inputs and outputs simultaneously in non-radial DEA models was presented in [83]. Furthermore, in [80] a CCR-DEA model was extended to a DEA-like model able to deal with undesirable inputs and outputs. In [69], authors have discussed a general approach of deriving DEA models to handle undesirable inputs and outputs without transferring undesirable data, such as in [81]. Including undesirable inputs and outputs, DEA has been extensively represented and used in environmental fields, such as energy and environmental efficiency. Additionally, a large number of papers have focused on the evaluation of transport energy or environmental efficiency [73].

Considering the efficiency of TCIS on utilization of railway capacity through the transportation process, undesirable outputs of TCIS functioning could appear, such as failures of the system. If inefficiency is present, the undesirable output should be reduced to improve inefficiency, that is, the role of TCIS on utilization of railway capacity, which means that undesirable and desirable outputs should be treated differently when we evaluate the impacts of TCIS on efficient railway capacity use. Based on the paper [84] regarding energy efficiency, production process, desirable and undesirable outputs are jointly produced by consuming both desirable and undesirable inputs, where x, e, y and u are vectors of energy inputs and non-energy inputs (i.e., here undesirable inputs and desirable inputs), desirable outputs and

undesirable outputs, respectively. Therefore, the joint production process can be represented as $T = \{(x, e, y, u):(x, e) \text{ can produce } (y, e)\}$. Based on this T reference technology, radial model, modified-radial and non-radial models such as the Russell measure model, Tone's slack-based model, range adjusted model and directional distance function model are used in energy efficiency and carbon emission efficiency in literature. Additionally, there are four types of returns to scale (RTS) such as constant RTS (CRS) which is the most used RTS category, non-increasing RTS (NIRS), non-decreasing RTS (NDRS) and variant RTS (VRS), where each of them reflects reference technology [73].

The radial model presented in [84] aims at reducing energy inputs as much as possible for the given level of non-energy inputs, desirable and undesirable outputs. Since the radial model has weak discriminating power in energy efficiency comparisons and does not consider energy mix effects, non-radial models for energy efficiency evaluation is also proposed in [84, 85]. They have presented application of non-radial DEA models for energy efficiency evaluation considering undesirable outputs and maximized energy-saving potential, all under CRS, NIRS and VRS. For example, if in model (M) instead of limitation (5) we write $\sum_{k=1}^{K} \lambda_k \leq 1$, $\sum_{k=1}^{K} \lambda_k \geq 1$ ili $\sum_{k=1}^{K} \lambda_k = 1$ we receive non-radial model under NIRS, NDRS and VRS, respectively. However, their non-radial models also attempt to reduce energy inputs as much as possible for the given level of non-energy input, desirable and undesirable outputs. In other words, their non-radial models do not consider reduction of undesirable outputs.

Furthermore, radial and non-radial DEA models for evaluating DMUs total-factor *energy and environmental efficiency* have been presented in [74]. In order to overcome the discriminating power of the radial model, following [86, 87] in [74], the radial DEA model for energy and environmental efficiency evaluation has been extended to a non-radial model. Assuming that there are K DMUs, and each DMU has n desirable inputs (non-energy inputs) and l undesirable inputs (energy inputs) in order to produce m desirable outputs and j undesirable outputs denoted, respectively, as $x = (x_{1K}, ..., x_{nK})$, $e = (e_{1l}, ..., x_{LK})$, $y = (y_{mK}, ..., y_{mK})$, $u = (u_{1K}, ..., u_{JK})$, the non-radial DEA model denoted (M) is the following:

$$min \frac{1}{2}\left(\frac{1}{L}\sum_{l=1}^{L}\theta_l + \frac{1}{J}\sum_{j=1}^{J}\theta_j\right)$$

s.t.

$$\sum_{k=1}^{K} \lambda_k x_{nk} \leq x_{n0}, n = 1, ...N \tag{1}$$

$$\sum_{k=1}^{K} \lambda_k e_{lk} \leq \theta_l e_{l0}, l = 1, ...L \tag{2}$$

where

$$\sum_{k=1}^{K} \lambda_k y_{mk} \geq y_{m0}, m = 1, ...M \tag{3}$$

$$\sum_{k=1}^{K} \lambda_k\, u_{jk} \;=\; \theta_j\, u_{j0},\, j \;=\; 1, \dots .J \tag{4}$$

$$\lambda_k \;\geq\; 0,\, k \;=\; 1, \dots .K. \tag{5}$$

This non-radial model (M) could be projected for evaluation of efficiency of TCIS in utilization of railway capacity. When compared to other non-radial models mentioned in the literature, the non-radial model (M) proportionally decreases the number of undesirable inputs and undesirable outputs as much as possible for the given level of desirable inputs and desirable outputs. The optimal values **of unified efficiency** are in the interval between 0 and 1. An entity with a higher value of efficiency has better efficiency in terms of the degree of the role of TCIS on capacity consumption as compared to others entities.

In the case of the non-radial DEA model (M), if the entity has an objective function equal to 1 it means that the entity is the best, located on the frontier, and could not reduce undesirable input and undesirable output. Such a non-radial model (M) could be applicable for evaluation of the efficiency of TCIS in railway capacity utilization because it has a relatively strong discriminating power and capability of expanding desirable outputs, while simultaneously reducing undesirable outputs. Additionally, **unified efficiency** can be calculated through decision-maker specified weights assigned to each of these two efficiency scores and depends on the preferences between undesirable inputs utilization and undesirable outputs. In the model proposed in [74], the weights were set to 1/2. Hence, besides additional widely used non-radial DEA models such as Slack-based models, Russell measure models and Directional distance function, in this chapter non-radial DEA model was chosen due to its ability to use different non-proportional adjustments, decision-maker specified weights assigned to each efficiency score, and because of its ability to proportionally decrease the amounts of inputs and undesirable outputs simultaneously as much as possible [73, 74].

4.4. Selection of case studies/DMUs and variables

In order to apply the non-radial DEA model, one of the most important steps is the selection of inputs and outputs, as well as classification of them as desirable and undesirable. Also, in [51], it was pointed out that the first point in assessing the performance improvements deriving from a better signaling system is to set what values have to be chosen for comparison.

One of the most traditional measures in railway capacity evaluation is the number of trains that travel in each corridor in a given time. However, in practice, there are different metrics that are equally important and could be used in capacity analysis [8]. Also, capacity should be analyzed in relation to the railway's primary mission, which is the transportation of freight and passengers [88]. Consequently, capacity can be evaluated through measures of network performance such as number of trains, number of wagons, number of pieces of cargo, number of passengers.

As can be seen from the literature review, different merits can be applied for evaluation of impact of TCIS on the railway capacity. However, mainly based on the available data, only limited merits were selected within this chapter. Therefore, based on the above reviewed factors that affect railway capacity, data availability and the fact that railway capacity can be described by other

indicators, for the purpose of evaluation efficiency and influence of TCIS on capacity utilization, desirable and undesirable inputs and outputs were proposed. First, because railway transportation can be represented as a production process, as desirable inputs, *length of railway network (DI1)* and *number of trains (per day) (DI2)* on the railway network were selected because they represent timetable indicators. As outputs of production process of railway transportation realized *freight kilometers (DO1)* and *passenger kilometers (DO2)* [88] were included in non-radial DEA model as desirable outputs. It is clear that higher value of DO1 and DO2 capacity was increased which is happening on the liberalized railway markets. Therefore, capacity is the maximum amount that can be produced in relation to the limiting constraints from infrastructure, rolling stock or staff [88]. Consequently, as undesirable input, which is close to the functioning of TCIS, *number of failures of the whole system or its subsystem (UDI)*, was proposed. Then, as an undesirable output, *punctuality of the trains (UDO)*, which is the result of system failures, was selected.

A second step of DEA methodology is the selection of comparable DMUs. For the application of the non-radial DEA model and consideration of the results of the model, based on the data availability for defined inputs and outputs, Serbia and Austria with their own TCIS as case studies were selected.

DMUs of selected case studies represent years. For each Serbian DMU, real data were used. Data for indicators such as *number of trains (per day)* and *punctuality of the trains* were collected from planned and realized timetables. For the *number of failures*, data were collected from the evidence of Serbian railways, while realized *freight and passenger kilometers* and *length of railway network* data were extracted for Serbian statistics.

Real data for the Austria case, published by OBB [89] were used only for 2015 and were collected for *length of railway network* and *number of trains (per day)* while data for *freight and passenger kilometers* Eurostat was used. However, data for *number of failures* were assumed because of missing data for that indicator. Data for other years were assumed due to unavailability of data for each year. All data used can be seen in **Table 1**.

DMUs	Serbia case study						Austria case study					
	DI1	DI2	DO1	DO2	UDI	UDO (%)	DI1	DI2	DO1	DO2	UDI	UDO (%)
2006	3819	1510	684,110	4232	55	40	9646[*]	6327[*]	110,778	8907	8	90[*]
2007	3819	1515	687,002	4551	43	55	9646[*]	6329[*]	115,526	9167	7	95[*]
2008	3819	1502	583,071	4339	38	60	9646[*]	6345[*]	121,579	10,365	7	95[*]
2009	3819	1430	522,033	2967	35	65	9646[*]	6332[*]	98,887	10,184	9	80[*]
2010	3819	1431	521,933	3522	39	60	9646[*]	6340[*]	107,670	10,263	10	85[*]
2011	3819	1431	540,911	3611	34	70	9646[*]	6340[*]	107,587	10,778	7	95[*]
2012	3819	1430	539,727	2769	23	80	9646[*]	6339[*]	100,452	11,211	6	96[*]
2013	3819	1433	612,495	3022	34	70	9646[*]	6330[*]	95,449	11,804	8	90[*]
2014	3819	1420	452,963	2988	27	80	9646[*]	6335[*]	98,281	11,981	7	95[*]
2015	3739	1436	508,678	3249	30	80	9646	6340	97,642	12,104	5	96.3

[*]Denotes assumed data.

Table 1. Data used for non-radial DEA model.

4.5. Results of non-radial DEA model and sensitivity analysis

With the aim to present the applicability of the non-radial DEA model in measuring the efficiency of TCIS on railway capacity utilization, using the real and assumed data, results of the application through case studies are presented in **Table 2**. All the results were obtained using Excel Solver. Based on them, it could be concluded that the non-radial DEA model can be applied for evaluation efficiency and influence of TCIS on railway capacity utilization. Results represent efficient and non-efficient DMUs, that is, years in which the influence of TCIS on capacity utilization was higher or lower. Since the real data were collected only for the Serbian case study, the results are valid. On the contrary, the results of the Austrian case study are not valid because we used the real data only for 1 year, and all other data were assumed. Therefore, the second case study was used only as an example in order to check the applicability of the non-radial DEA model.

However, in order to check the stability and behavior of the non-radial DEA model, the sensitivity analysis was conducted for each case study (for results see **Table 2**). Consequently, the ideal way, which can be related to sensitivity analysis, is therefore to vary some parameters while monitoring the relative movement of efficiency changes [51]. Like, for example, to vary the indicators, that is, UDI and UDO – while observing the results of the influence of TCIS on railway capacity consumption. Therefore, the sensitivity analysis was conducted through data variations applying "approach II" through "development model" [90]. Sensitivity analysis was made for certain percentages of perturbation (10, 20 and 50%) until the status of at least one DMU was changed from inefficient to efficient or vice versa [77]. For efficient countries, both undesirable inputs and outputs were increased and simultaneously decreased for the inefficient one. After each data perturbation, the calculation performed by Excel Solver and the results obtained are represented in **Table 2**. From the results, it can be

	Serbia case study				Austria case study			
	Results of non-radial DEA model	Sensitivity analysis of non-radial DEA model			Results of non-radial DEA model	Sensitivity analysis of non-radial DEA model		
DMUs		10%	20%	50%		10%	20%	50%
2006	1	1	1	1	0.8795	0.928	0.928	0.928
2007	1	1	1	1	0.9502	1	1	1
2008	0.9764	1	1	1	1	1	1	1
2009	0.7882	0.8807	0.8807	0.8807	0.8412	0.898	0.898	0.898
2010	0.7813	0.8795	0.8795	0.8795	0.8296	0.8871	0.8871	0.8871
2011	0.8134	0.9059	0.9509	0.9505	0.9107	1	1	1
2012	1	0.8531	0.6951	0.3475	0.9274	1	1	1
2013	0.914	1	1	1	0.8279	0.951	0.951	0.951
2014	0.7516	0.8215	0.8215	0.8215	0.8684	1	1	1
2015	0.7851	0.8604	0.8604	0.8604	1	1	0.9999	0.9999

Table 2. Results and sensitivity analysis of application of non-radial DEA model.

concluded that the efficiency score was improved for all inefficient years. With 10 and 20% of decrement in data for the Serbia, firstly inefficient years 2008 and 2013 became efficient, while the efficiency score was changed for efficient year 2012 after the 10% of increment in data. In terms of the Austrian case with 10% of decrement in data inefficient DMUs, that is, years 2007, 2011, 2012 and 2014 – became efficient, while for 2015 the efficiency score was changed with 10% of increment in data.

Taking into account the results of sensitivity analysis, it can be noted that sensitivity analysis shows some anomalies or weaknesses in the non-radial DEA model. The first is related to the sensitivity of the efficiency score with a smaller percentage of modifications in undesirable input and output. In the case of inaccurate data, the model can provide an unrealistic picture regarding the best DMUs. Another weakness of the model can be related to the correctness of the results depending on the number of variables included. It should be noted that with a higher percentage of data modifications the model would provide a picture related to more significant changes of the efficiency score. Also, it is clear that without an adequate classification of variables as inputs and outputs, results can be inaccurate.

5. An overview of the applications of MCDM in railway engineering

Based on the searches performed in Scopus and Science Direct databases, in the literature application of different MCDM in railway engineering such as AHP, ANP, DEA, TOPSIS, VIKOR and DEMETAL can be found, while DEA, used in terms of capacity evaluation, can be found also in other fields of railway. A detailed literature review related to application of DEA in the railway can be found in [6]. These methods were used alone or in combination with other MCDM. Also, in the literature some multicriteria hybrid approaches in railway engineering could be found. For solving multicriteria decision problems such as railway capacity, in [91] the RECIFE software as a multicriteria decision supports system for the evaluation of railway capacity at the station or junction level.

5.1. Analytic hierarchy process (AHP)

In the literature, the analytic hierarchy process (AHP) appears as one of the most commonly used MCDM. According to [92], the major multi-criteria decision methods used for dealing with railways management problems were AHP and ANP. AHP is used also to get indicators' weight values in [93], for determination of weights of each index [94], in evaluation of the railway infrastructure objects from the perspective of traffic safety risk [95] and to find the weights for the selection criteria in selecting the most appropriate supplier [96]. Through installation of the Train Conformity Check system (TCCS) that can detect and alert dispatchers about several dangerous or damaging defects on rolling stock [97] have applied AHP to evaluate the optimal locations to install a TCCS on a railway section.

In order to identify the most suitable manufacturer of rail vehicles for the UK infrastructure project, High Speed 2 in [98] applied AHP for effective comparison of the four primary rolling stock manufacturers: Bombardier, Siemens, Hitachi and Alstom.

In improving the public transport system of Istanbul through the planning of the rail transit network in [99], AHP was used in evaluation of the final three alternatives. In terms of the quality of railway passenger transportation, AHP was used for determination of weights for criteria [100] and indictors [101, 102] and for the different maintenance actions in the railway infrastructure [103], relative weights of quality of service criteria in the high-speed railway wireless communication networks [104], weights of 16 criteria of the quality of the trip by train [105]. In [6], AHP was used to develop a model for evaluation of TCIS and their subsystems, as well as KPTs in terms of sustainability.

Besides the application of traditional AHP in the railway field the papers that aimed at modeling the fuzziness in the AHP which allows inclusion of human experts and their communication of linguistic variables [106] are found. In combination with the fuzzy set theory, Li [107] has applied AHP to select the best design scheme of the railway freight car. In [108], the Fuzzy AHP was used to develop a risk assessment system for evaluating both qualitative and quantitative risk data and information associated with the safety management of railway systems. A hierarchical customer satisfaction framework was made by [109] where fuzzy AHP has been applied for calculation of weights of main criteria. After application of fault tree analysis to analyze historical general accidents in railway transportation in [110], AHP was employed to analyze relationships between the factors and general accidents. Group fuzzy AHP was used by [111] for ranking and selection of key performance indicators of railway control rooms.

5.2. Analytic network process (ANP)

The adoption of ANP for the evaluation of maintenance strategy for rolling stock of railway system operators formed by various combinations of preventive maintenance (PM) and corrective maintenance (CM) was presented by [112]. Using ANP in [113], the methodology was developed and applied to a technical maintenance project for the Spanish National Railway Infrastructure company for measuring stakeholders' influences within a project. For the historic Alishan Forest Railway in Taiwan, in [114] the analytic network process (ANP) was used in evaluation of different revitalization strategies based on the various factors and the interactions of those factors.

5.3. Technique for order preference by similarity to ideal solution (TOPSIS)

In evaluation of high-speed transport systems where alternatives are represented as High-Speed Rail and Transrapid Maglev, TOPSIS was applied in [115] for selection of the preferable alternative. The TOPSIS method with multilevel grey evaluation (MGE) was employed by [116] to evaluate the overall performance of passenger transfer at large transport terminals. Fuzzy TOPSIS with failure mode and effect analysis was proposed by [117] for determination of the closeness coefficient of each failure mode of metro door fault criticality. For measurement of a service quality of rail transit lines in combination with statistical analysis, trapezoidal fuzzy numbers has been adopted, Fuzzy-TOPSIS [118].

5.4. Data envelopment analysis (DEA)

In order to recognize changes in the efficiency and productivity of railway freight transportation in Europe, [119] applied DEA to analyze different European countries from 1980 to 2003.

For analyzing and comparing the synthetic indices of accessibility for evaluation impacts of high-speed trains on European cities [120] considered DEA and Principal Component Analysis (PCA) which were employed in the their previous two studies. Using a two-stage bootstrapped data envelopment analysis (DEA) with incorporation of transaction costs in order to assess the desirability of vertical separation in [121] authors compared 43 Swedish, German and British train operating firms.

The methodology for defining, measuring and analyzing the capacity utilization by DEA in the passenger railway operation sector and freight sector was developed by [6]. A DEA cross evaluating method based on grey incidence analysis was adopted by [122] to evaluate and estimate the efficiency of shunting locomotives operation in train service depots.

For evaluation of the inter-regional railway operation performance for 30 provinces in China, [123] adopted the SUPER-SBM DEA method dealing with uncontrollable factors. By DEA, in [66] the relative operational efficiency of 24 European railways in capacity utilization was studied.

Throughout the investigation of the potential impacts on rail accessibility across the Europe for different scenarios, in [119] the DEA method was employed. Working on the real-time optimization of train scheduling decisions at a complex railway network during congested traffic situations, [124] used DEA in evaluating the relative efficiency of the different optimization formulations.

In order to use an adequate approach to quantify and rank the relative performance and efficiency of stations, in [125] two novel models of the DEA method as a new tool for analyzing macro and micro capacity utilization at stations were suggested. In order to measure the success of the liberalization process of railway transportation in [126], DEA was used for estimation of technical effectiveness of railway performance; [127] used Fuzzy DEA to evaluate the efficiency of the rescheduled timetable in terms of delay minimization and robustness maximization.

5.5. VIKOR and ELECTRE methods

In the methodology of route selection applied for railway route planning and design in [128], Vlsekriterijumska Optimizacija I Kompromisno Resenje (VIKOR) was used for the selection of the most favorable railway route. Within the framework developed for measuring the level of customer satisfaction related to rail transit network (metros, trams, light rail and funicular) in Istanbul, in combination with other techniques in [129] applied VIKOR with interval type-2 fuzzy sets to obtain the best customer satisfaction level of rail transit network based on average and the worst group scores among the set of alternatives. VIKOR, with an intuitionistic fuzzy set, was also introduced and employed by [130] for CRH2 high-speed train bogie system operation safety assessment.

Based on the literature review related to multicriteria decision analysis in transportation, through using a screening method and ELECTRE I, in [131] selection of a high-speed rail corridor/route that can be useful in planning high-speed rail in Malaysia was provided.

5.6. Hybrid/combined MCDM approaches

In the literature some combinations of MCDM approaches in railway engineering could also be found. For example, in [132] authors integrated DEA and AHP with computer simulation for railway system improvement and optimization. Using AHP and DEA, a selection of the optimum site for a railway station was presented in [133]. In [134], the evaluation of world railways performance with a fuzzy dynamic multi-objective DEA model was presented.

In the two-phase model for ranking railway projects from different railway subsystems in [135], TOPSIS was used with AHP in [136] an improved Dempster-Shafer theory (DS)/AHP method for the evaluation of hazard source was provided. For the purposes of evaluation and selection of optimal locations for freight villages, authors of [137] developed a GIS-ANP-TOPSIS framework. For selection of the most appropriate maintenance policy, an integrated MCDM approach was developed by [138] on the basis of FANP technique and in combination with the DEMATEL. In [139], ANP and DEMETAL were used to determine the leading accident casual factors and to analyze the influence of the relationships of human and organization factors.

6. Conclusions and future work

This chapter focused on the introduction of a new approach in efficiency evaluation of TCIS regarding the influence on improvement of capacity utilization. For the purpose of efficiency evaluation of TCIS, the non-radial DEA model was proposed and employed. The efficiency evaluation of TCIS influence on improvement of the capacity utilization with the non-radial DEA model was conducted by including desirable and undesirable inputs, as well as desirable and undesirable outputs. The evaluation was tested through two case studies, that is, Serbian and Austrian for the period from 2006 to 2015 mainly based on the assumed data for the Austrian case, where years represent DMUs. The results of the non-radial DEA model showed the best efficiency year in terms of the influence of TCIS on capacity utilization, as well as those with low(er) efficiency.

Based on the performed sensitivity analysis, it can be said that the non-radial DEA model is valid and can be applicable for the evaluation efficiency of TCIS influence on capacity utilization for different levels, that is, overall network or particular line. However, there is a significant sensitivity to data for a smaller data variation that cause reduced stability of the model. In the case of inappropriate and missing data, results can be different – it is certain that results of the model will be different because sensitivity analysis showed instability with a lower data variation. Overall, these weaknesses can affect the results of the non-radial DEA model and provide a thankless picture regarding efficiency in terms of the influence of TCIS on railway capacity utilization. However, in the case of accurate data and selection of appropriate inputs and outputs in accordance with the aim of the evaluation, the proposed new methodology could be a good tool for efficiency evaluation of TCIS influence on capacity utilization.

Through empirical study, it can be shown that the non-radial DEA model, employed using an accurate set of data, can provide an evaluation of the efficiency of the TCIS influence on capacity utilization both at the macro and micro levels, as well as benchmarking for different levels. The evaluation of other factors and their impacts of TCIS on capacity utilization are also possible with the non-radial DEA model.

As future work, based on a comprehensive and accurate set of data, the proposed methods can be used with different variables/criteria and tested in order to check their validity. Also, as a part of the future work, methods can be applied on the micro level for evaluation of the influence of TCIS on capacity utilization for a particular line. Moreover, with this MCDM, the evaluation, measuring and comparison of railway capacity consumption for different concepts of capacity can be conducted.

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