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Capacity Utilization in European Railways: Who is the fairest of them all?

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ABSTRACT

At the strategic level, railways currently use different indices to estimate how ‘value’ is generated by using railway capacity. However, railway capacity is a multidisciplinary area, and attempts to develop various indices cannot provide a holistic measure of operational efficiency. European railways are facing a capacity challenge which is caused by passenger and freight demand exceeding the track capacity supply. In the absence of a comprehensive railway capacity manual, methodologies are needed to assess how well railways use their track capacity. This paper presents a novel and unprecedented approach for this aim. Relative operational efficiency of 24 European railways in capacity utilization is studied for the first time by data envelopment analysis (DEA). It deviates from previous applications of DEA in the railway industry that are conducted to analyze cost efficiency of railways. Six DEA models quantify various aspects of micro, macro and quality of railway capacity utilization in these countries. New inputs like gross domestic product, population and area of the country help to provide a better picture of the status of railways. Passenger satisfaction data about different aspects of railway services in European countries has recently been quantified by European commission and are used for the first time in the literature. Invaluable insights can be inferred from the results which can provide a ground basis for railway practitioners and policy makers.

INTRODUCTION

"The stereotypical image of railways is of an industry in long-term decline, a nineteenth century technology struggling to adjust to the twenty first century. As with many stereotypes this is a gross simplification (*1*)." Railways in Europe as well as North America are facing a so-called "capacity challenge" due to growth in passenger and freight demand outweighing growth in the track capacity supply (*2, 3*). In Europe, statistics show a total increase of 32% in tonne-km of freight transported by rail and an 9% increase in rail passenger-km between 2001 and 2010 (*4*) . During this time, railway infrastructure has increased by just 5% (Table 1).

Table 1- Growth in rail passenger, freight and infrastructure across Europe. Data source:(*4*)

Year	2001	2010	2001	2010	2001	2010
Item	Passenger-km (billion)		Tonne-km (billion)		Line-km	
Value	575.3	626.2	1861.0	2,454.4	353,170	370,387.9
Growth (2010/2001)	+8.86%		+31.88%		+4.88%	

Efficient capacity utilization is a primary concern for railways around the world due to the increasing demands for railway transportation in the face of road congestion, higher fuel costs and concerns for sustainable transportation (*5*). Road and railway are the two modes of transportation that face capacity constraints on their guideways along with nodal capacity constraints which is an issue for all modes of transportation. However, contrary to road transportation which is replete with research on various aspects of capacity, the need for a comprehensive railway capacity manual is greatly felt in railway transportation as stated by the Rail Capacity Joint Subcommittee of the Transportation Research Board (TRB) (*6*). A comparison between the status of road and railway capacity manuals are presented in Table 2.

Table 2-Capacity manual for road and railway transportation(*7*)

	Road	Railway
Name	Highway Capacity Manual	Capacity leaflet
Published by	Transportation Research Board (TRB)	International Union of Railways (UIC)
First edition	1950	2004
Latest edition	2010	2004
Number of pages	1650	24

The efficiency of railway capacity varies with different railways. This raises the question of which countries use railway capacity most efficiently and how do they do it. This piece of research aims to develop a methodology for comparing railway capacity utilization in different railways to find the best practices and their underlying causes, which can be used as benchmarks for other railways to improve their capacity utilization. European railways have been chosen for conducting a case study as they share a rather similar nature.

RESEARCH ON CAPACITY UTILIZATION IN RAILWAYS

In the past few years, railway researchers across the globe have tried to respond to the need for railway capacity research by developing various methodologies for defining, measuring, analyzing, improving and controlling capacity utilization. Major recent studies in this field are summarized in Table 3.

WHY DEA IS NEEDED FOR CAPACITY ANALYSIS

The literature of railway capacity analysis includes four main categories of methodologies: operations research, simulation, analytical methods and parametric models. Each of these methods satisfies one of the special needs in the sequence of line planning which as suggested by Vromans (*8*) are: market demand analysis, line planning, timetabling, rolling stock planning, shunting and crew planning. The realm of operational planning in railways is rich in numerous studies on timetable design, infrastructure modeling, timetable stability, delay analysis, rescheduling, train routing, train formation, crew planning, etc. as reviewed by Assad (*9*), Cordeau et al. (*10*), Tornquist (*11*), Hansen et al. (*12*) and Lusby et al. (*13*).

However, as we move from operational planning towards tactical and strategic planning, the number of quantitative studies dwindles, leaving railway practitioners, managers and policy-makers an insufficiently solid basis on which to make informed decisions. Data envelopment analysis is a powerful tool 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.) are needed.

At the strategic level, railways currently use different indices to estimate how 'value' is generated by using railway capacity. These indices and metrics have been reviewed by Dingler (*14*) and Khadem Sameni et al. (*15*). However, railway capacity is a multidisciplinary area, and attempts to develop specific indices fall into the trap of the so-called "index number problem". As the co-winner of the Economics Nobel prize in 1969 has put it:

"The index-number problem arises whenever we want a quantitative expression for a complex that is made up of individual measurements for which no common physical unit exists. The desire to unite such measurements and the fact that this cannot be done by using physical or technical principles of comparisons only, constitutes the essence of the index-number problem and all the difficulties centre here." (*16*) DEA aims to "provide a satisfactory measure of efficiency that takes into account all inputs yet avoids index-number problems" (*17*). There is a long history of economists using DEA in railways to analyze economic efficiency as reviewed by Recently, DEA has been applied to railway capacity and provided promising results, such as the studies conducted by Khadem Sameni and Preston (*5, 18*) to improve capacity utilization at railway stations and by passenger-train operators in the United Kingdom.

Table 3- Major research on railway capacity utilization (*18*)

Author(s)	Theme	Main Contributions	Type	Volume (pages)	Country of case studies
Kieran (*19*)	Pricing railway capacity	• Comprehensive study of track access charges in Europe and North America • Suggesting a track access pricing process for Canada	Research project	38	Canada
Cambridge Systematics (*3*)	Improving capacity utilization	• Identifying level of service for primary corridors in the US railway network • Estimating future capacity improvements needed	Research project	69	United States
Harrod (*20*)	Improving capacity utilization	• A new practical model for master scheduling of a freight railway by considering line capacity constraints, multi commodity flows and network value	PhD thesis	215	United States
Abril et al. (*21*)	Improving capacity utilization	• Survey of capacity analysis methods • Developing a system called MOM that can produce improved timetables for off-line and on-line scenarios, analyse network capacity utilization and timetable robustness.	Journal Paper	33	Spain
Lai (*22*)	Improving capacity utilization	• Developing a decision support system named RCET that can optimise investing in different capacity expansion schemes	PhD thesis	184	United States
Landex (*23*)	Measuring and analysing capacity utilization	• Thorough investigation of the UIC 406 method • Studying trade-offs in the capacity balance	PhD thesis	218	Denmark

Lindfeldt (*24*)	Analysing and improving capacity utilization	• Developing the SAMFOST mathematical model that can calculate crossing time for single tracks based on infrastructure configuration, rolling stock, timetable and delays. It can be used to assess alternative infrastructure improvements and their effects on capacity utilization . • Developing the TVEM model that can systematically generate and compare different timetable variants for double track lines to evaluate their effects on capacity utilization	PhD thesis	228	Sweden
Roberts et al.(*25*)	Improving capacity utilization	• Matrix of capacity interdependencies • New model for choosing capacity enhancement measures	Research project	84	United Kingdom
Pudney et al. (*26*)	Measuring, analysing and improving capacity utilization	• Survey of different capacity interrelated indicators, capacity analysis methods and capacity improvement techniques	Research Project	45	Australia
Kontaxi and Ricci (*27*)	Measuring and analysing capacity utilization	• Comprehensive overview of capacity measuring methodologies since 1950s • Developing RailCAT, an integrated online capacity calculating tool	PhD thesis	Underway	Italy
Khadem Sameni (*28*)	Defining, measuring, analyzing, improving and controlling	• Developing a railway capacity manual for different aspects of defining, measuring, analyzing, improving and controlling capacity utilization in passenger and freight sector	PhD thesis	221	United Kingdom

STRUCTURE OF RAILWAYS IN EUROPE

European railways have rather similar structures. The operational and infrastructure in European railways are separated following the EU directive 91/440 (*29*). This is usually referred to as "vertically separated" structure in which government owns and maintains the railway infrastructure and dictates the policy. The capacity of infrastructure is allocated to private and national passenger and freight companies to offer services to the public. For instance DB(Deutsche Bahn) and NS (the primary passenger operator in the Netherlands) are examples of national companies. Railways in the North America are "vertically integrated" in which infrastructure is usually owned by the operator. An overview of the main features of railways in Europe and the USA are presented in Table 4. Two main railways deviate from the Euopean theme of vertically segmented railways and they are vertically merged. These are DB and ÖBB (national Austrian railways) are vertically merged.

Table 4- Overview of railways in Europe and the USA (*30*)

	Europe	**USA**
Main focus	Passenger	Freight
Timetable	Thorough timetable	Most often no exact timetable
Infrastructure owner	Most often state or state owned infrastructure manager	Mainly privately owned by the operator
Operation and infrastructure	Railway operation is separated from infrastructure management as a requirement of liberalisation stated by the European Union laws. (vertically segmented railways)	Railway operation and infrastructure management are merged together. (vertically merged railways)
Signalling	High technical level – often with ATC/ATP	Often simple signalling
Distance	Short/medium distance	Long distance
Length of trains	Varies	Usually very long
Traction	Electric, some diesel	Diesel

For obvious reasons, there are slight differences in the way railways are run in various countries across Europe. For instance, the number of operators and their share in total railway transportation can vary in different countries and can be few with a concentrated market share as in France as opposed to many operators with a distributed share as in the UK(*31*). There are also differences in the system for charging for rail infrastructure capacity, as summarized by Hylen (*32*):

- Scandinavian approach: practised in Sweden, Finland and Denmark. It is characterized by: low variable charges are based on short run marginal cost; infrastructure charges are estimated by comparisons with other modes of transportation; governments contribute the difference between income and infrastructure costs.

- Adjusted average cost: practised with some variations in Germany, France and Austria. Targeted revenue through adjusted variable costs (substantially more than short run marginal costs) is raised depending on the level of government contributions.
- British approach: Very high fixed costs but variable costs at or below short run marginal costs. costs.

A brief overview of European railways is presented in Table 5. Due to some missing data, Greece could not be included in the case study. The DEA models presented in this paper are applied to a case study of European railways in 2010. They provide a novel and unprecedented approach to railway capacity analysis. DEA models are presented in two categories. The first category addresses the quantity of capacity utilization (at macro and micro levels) and the second category investigates the quality of capacity utilization in European countries. In the first category of models, new inputs such as GDP and population has been used for the first time in the literature. The second category of models is totally novel as it uses quantified satisfaction of passengers across Europe as outputs which has recently been studied and published by European commission (*33*).

Table 5 – Synopsis of railways in Europe

Country	Year the first line opened (*34*)	Name of the main infrastructure owner	Total line-km (*4*)	Percentage of double track or more lines-calculated based on (*4*)	Percentage of electrified line-calculated based on (*4*)	Passenger-km in million (*4*)	Passenger modal split (*33*)	High speed lines (over 200km/h) exist? (*35*)
Belgium	1835	Infrabel	3578	77%	84%	10493	7%	Yes
Bulgaria	1866	NRIC	4098	23%	68%	2100	3.70%	-
Czech Rep.	1839	SZDC	9469	20%	34%	6553	7.60%	-
Denmark	1847	Banedanmark	2131	44%	29%	7405	8.60%	-
Germany	1835	DB Netz	33708	54%	59%	78582	8%	Yes
Estonia	1870	EVR	787	11%	17%	248	2.10%	-
Spain	1848	Adif	15317	34%	59%	22304	5.40%	Yes
France	1832	RFF	33608	57%	50%	86853	9.90%	Yes
Ireland	1834	Irish Rail	1919	26%	3%	1678	2.90%	-
Italy	1839	RFI	18011	47%	73%	44535	5.50%	Yes
Latvia	1862	LDz	1897	17%	14%	79	4.80%	-
Lithuania	1862	JSC	1767	22%	7%	373	0.70%	-
Luxembourg	1859	ACF	275	53%	95%	345	4.40%	-
Hungary	1846	MAV	7893	17%	37%	5398	11.80%	-
Netherlands	1839	ProRail	3016	66%	70%	15400	9.70%	Yes
Austria	1838	ÖBB Netz	5066	38%	67%	10306	11.20%	-
Poland	1842	PLK	19702	44%	60%	15715	5.20%	-
Portugal	1856	REFER	2843	21%	52%	3718	4.10%	-
Romania	1869	CFR	10777	27%	37%	5248	5.90%	-
Slovenia	1846	SŽ	1228	27%	41%	813	2.50%	-
Slovakia	1869	ZSR	3587	28%	44%	2291	6.70%	-
Finland	1862	Liikennevirasto	5919	10%	52%	3959	5.20%	-
Sweden	1856	Trafikverket	9957	18%	79%	6774	9.40%	-
United Kingdom	1825	Network Rail	31471	63%	40%	55020	7.50%	Yes

MACRO AND MICRO CAPACITY UTILIZATION MODELS

Khadem Sameni et al.(*7*) emphasize that capacity utilization has two aspects: macro and micro. Macro capacity utilization is at train level and considering them as black boxes (such as the UIC 406 timetable compression method and train-km) and the other is micro capacity utilization which looks into how efficiently these macro chunks of allocated capacity are utilized at micro level (such as passenger-km, tonne-km, etc.). Quality of capacity utilization is also an important issue: macro and micro capacity utilization might be very efficiently used (e.g. many trains run on the network and with high load factor) but at the expense of low quality of service (i.e. high primary and secondary train delays, passengers standing in trains, etc.). Finding the exact function between these aspects would be challenging such as the study by Khadem Sameni (*15*) which tried to find a profit function for the level of capacity utilization in an American case study. This is where DEA can help railway capacity analysis at tactical and strategic planning. Three models are suggested for analyzing macro and micro capacity utilization which are illustrated in Figure 1.

The first model is intended for macro capacity utilization. The aim of this model is to identify how well the potential for producing railway services in a country is actualized. For the first time in the DEA studies in railways, it uses Gross Domestic Product (GDP) as one of its inputs. GDP is the value of final goods and services that are produced in one country. GDP is defined based on geographic location whereas Gross National Product (GNP) is based on ownership hence GDP is suitable for the input of the model. The higher the GDP of a country, the more the opportunities exist for the railways to carry passengers and freight. The data for GDP was extracted from the World Bank website (*36*). The number of locomotives and total lines are two other inputs chosen to reflect the available infrastructure to carry railway services. The output of the model is chosen as train-km which provides better insights as compared to the number of trains.

The second model analyses micro capacity utilization. The aim of the model is to identify how efficiently the provided train services are used by passengers. Train-km is chosen as one of the inputs of this model as the more trains are run on the network and the loner they run, the higher is the opportunities for passengers to get on the trains. Another input of the model is population of the country. This input is used for the first time in DEA models developed in railways. It is needed as a proxy variable to reflect the potential passengers existing in a country. With the same level of train-km in a country, the higher the population, the higher chances of using trains as their mode of transportation. Passenger-km is an appropriate output to measure the quantity aspect of micro capacity utilization. The most important parameter to reflect the quality of the train services provided is punctuality and reliability. However, different railways across the Europe use different indices to measure their punctuality and reliability. For instance, the threshold for considering trains as delayed is five minutes in Great Britain, four minutes for Switzerland and three minutes for the Netherlands (*37*). Therefore, satisfaction with punctuality and reliability as perceived by passengers in that country are used. This output is the percentage of the surveyed passenger in the European Commission study (*33*) that stated they are either very satisfied or satisfied with the punctuality of the train services in their country.

There is another model for relative efficiency of European railways in micro capacity utilization (model 3) which analyses how passenger-km and tonne-km are packed in train-km.

QUALITY OF CAPACITY UTILISAITON MODELS

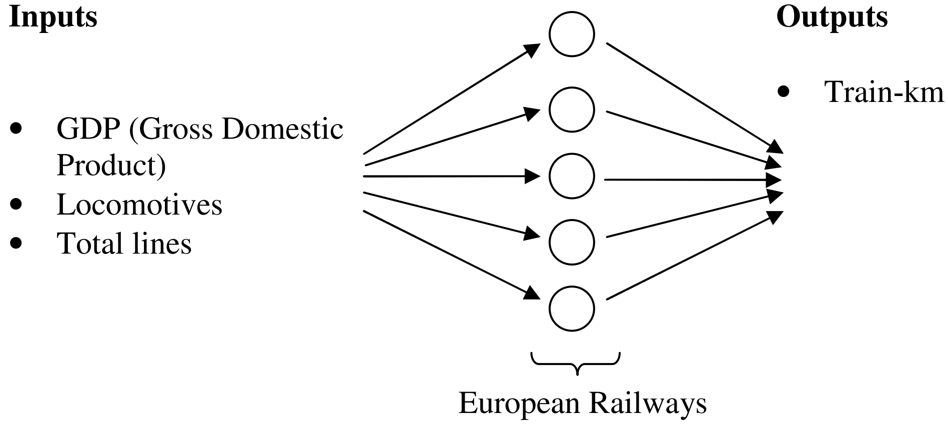
Three models (Figure 2) are suggested to quantify the relative efficiency of European railways for their quality capacity utilization. Satisfaction of passengers with various aspects of train services were used as outputs of the models. These statistics were extracted from the European Commission's recent study (*33*) .

The first model (model 4) measures how well train-km (input) is distributed in a country to produce satisfaction of passengers for the frequency of the train services in their country as well as satisfaction with connections with other train services as outputs. However, another input is needed to reflect how vast the country is as with the same level of train services, the bigger the country, the less the density of train services would be. Area of the country in square kilometres is chosen for this purpose which was extracted from the UIC statistics (*4*).

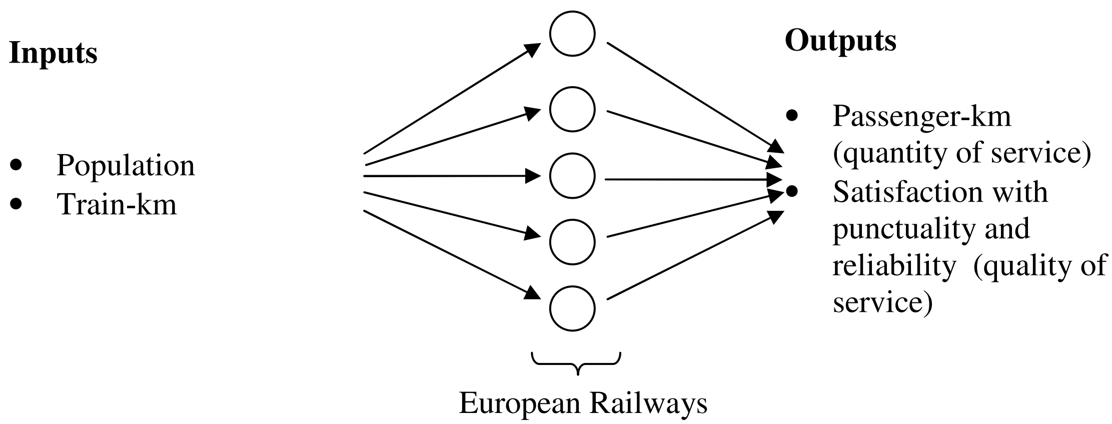
Perceived staff availability for passengers affects feeling of safety, security and being looked after in case of a problem or question. It is an important issue for attracting passengers to use railways (increasing micro capacity utilization). For the second quality model, average staff strength (*4*) and passenger carried (*4*) are chosen as the inputs. Outputs of the model are satisfaction with provision of information during the journey, satisfaction with availability of staff on trains and satisfaction with assistance for disabled or elderly in stations and onboard the trains.

The last model (model 6) quantifies the relative efficiency of European railways in providing clean and secure journey for their passengers. For this model, satisfaction with cleanliness and good maintenance of station facilities, satisfaction with cleanliness of rail cars and satisfaction with respondent's security in station are chosen as outputs.

Model 1- Macro capacity utilization



Model 2- Micro capacity utilization I



Model 3- Micro capacity utilization II

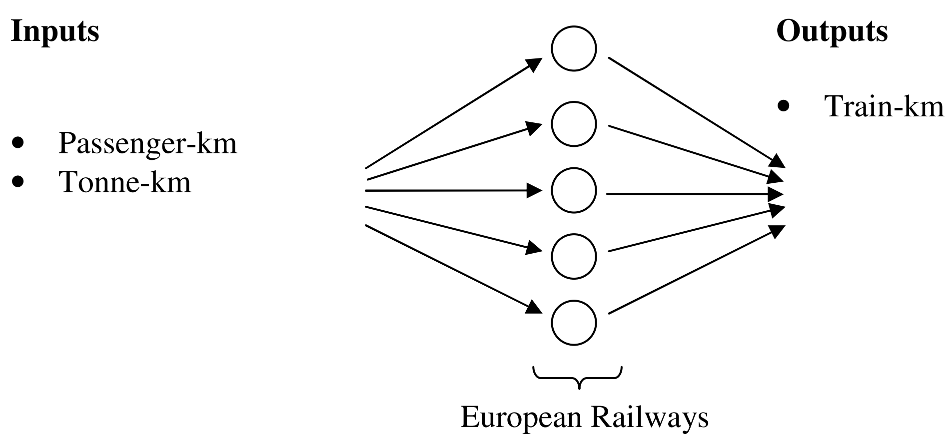
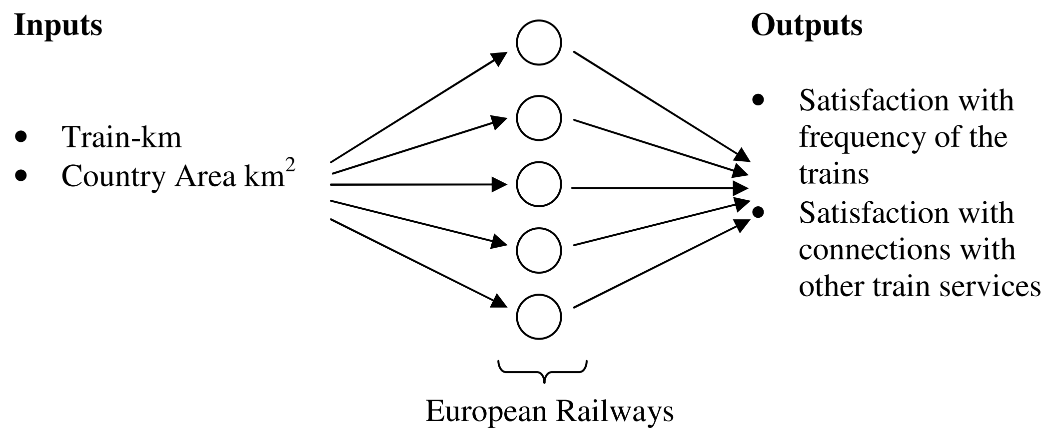
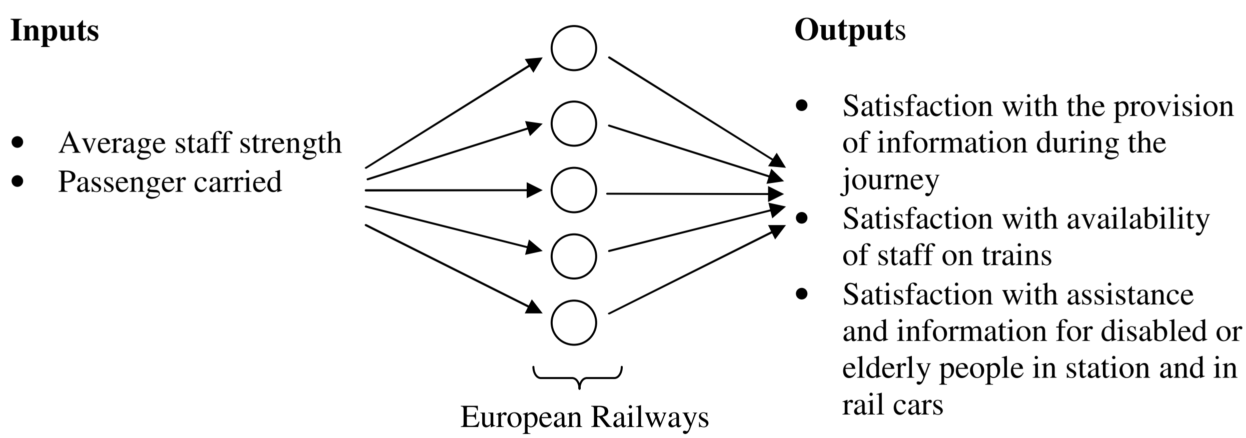


Figure 1- Macro and micro capacity utilization models

Model 4- Frequency and connection efficiency



Model 5- Staff Availability on trains



Model 6- Cleanliness and security efficiency

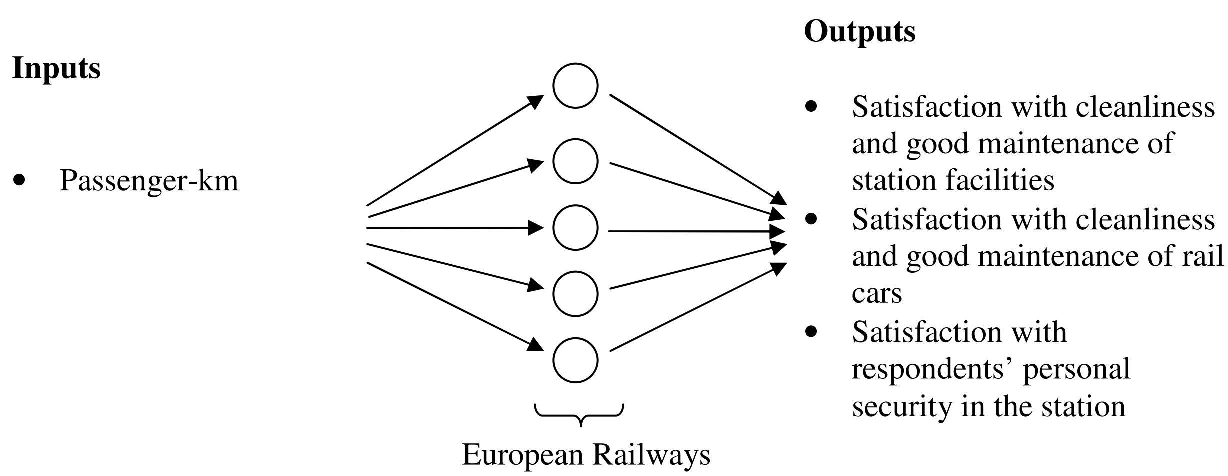


Figure 2- Models for Quality of Capacity Utilization

ANALYSIS OF THE RESULTS

The results of all the models are presented in Models were solved with variable returns to scale assumption by using PIM DEA-V3.0 software (*38*). Some interesting insights can be inferred from the results. The country that ranked at the top is Luxemburg which scores 100% relative efficiency in all models. This can be very well explained by 95% of the lines being electrified, having the world's second highest GDP, a very high human development index and small country which makes transportation very efficient.

The countries that have 100% efficiency for macro and micro capacity utilization are Denmark, Estonia, Latvia, Luxemburg, Slovenia and the United Kingdom. The size of the first five countries explains the results. In smaller countries, travelling by train (as opposed to flying or using a personal car) is more logical whether the purpose of trip is business or pleasure. It is also easier for railway authorities in a small country to provide efficient, high-quality, punctual and desirable services. The place of United Kingdom seems a bit odd at first sight. However several reasons make it justifiable. Railways originated from the UK and its people have special bonds with railways. Dividing the total line kilometres to the area of the country shows that the density of railway lines is the highest among all the European Countries studied in this case study. This makes railways accessible and convenient for travel. However, maintaining such a huge network with an old infrastructure comes at an immense cost. A recent study by Lovell et al.(*39*) contends "that Britain's rail infrastructure manager faces an efficiency gap of 40 per cent against European best practice and that train operating costs have also risen substantially, both because of rising factor prices (wages and fuel) and because of deteriorating productivity". However, the results of this study suggest that when the train services are produced, they are efficiently used. The problematic link of the chain is how and the cost that these services are produced. Having the most complicated structure of railway structure in Europe with many players who have different goals and distributed market share (*31*) puts the burden on government for maintaining the infrastructure at high cost and for paying enormous franchise payments to train operators. There is also a burden on passengers who have to pay for among the most expensive train fares in Europe.

On the low side of macro and micro capacity utilization are Hungry and Sweden which have the lowest percentage of double track lines. This is in line with the claim that "double track line often quadruples capacity"(*40*).

For the quality of capacity utilization models, Luxemburg and Estonia are on the frontier of efficiency and Ireland is the closest to it. At the lowest quality of capacity utilization (as perceived by passengers) are Poland, Bulgaria and Romania. Interpreting and discussing the exact underlying causes of this requires further research to investigate the correlation between efficiency scores and GDP per capita or the Human Development Index (HDI).

Table 6 - Results of all models

	Macro and micro capacity utilization				Quality of capacity utilization			
	Model 1	**Model 2**	**Model 3**	**Average**	**Model 4**	**Model 5**	**Model 6**	**Average**
Belgium	79%	75%	72%	75%	92%	94%	91%	93%
Bulgaria	100%	72%	76%	82%	70%	76%	62%	69%
Czech Rep.	100%	76%	100%	92%	95%	85%	75%	85%
Denmark	100%	100%	100%	100%	94%	84%	96%	91%
Germany	100%	93%	100%	98%	89%	67%	91%	82%
Estonia	100%	100%	99%	100%	100%	100%	100%	100%
Spain	66%	98%	90%	84%	96%	98%	100%	98%
France	71%	100%	60%	77%	85%	76%	88%	83%
Ireland	100%	96%	100%	99%	100%	100%	99%	100%
Italy	63%	87%	70%	73%	100%	90%	79%	90%
Latvia	99%	100%	100%	100%	70%	100%	100%	90%
Lithuania	70%	100%	95%	88%	75%	100%	100%	92%
Luxembourg	100%	100%	100%	100%	100%	100%	100%	100%
Hungary	24%	100%	19%	48%	89%	80%	80%	83%
Netherlands	100%	84%	43%	76%	97%	73%	89%	86%
Austria	100%	96%	68%	88%	97%	82%	95%	91%
Poland	84%	54%	61%	66%	53%	65%	58%	59%
Portugal	49%	100%	55%	68%	97%	100%	97%	98%
Romania	66%	58%	66%	63%	69%	79%	66%	71%
Slovenia	100%	96%	100%	99%	81%	100%	100%	94%
Slovakia	78%	87%	81%	82%	88%	87%	76%	83%
Finland	62%	68%	56%	62%	99%	84%	100%	94%
Sweden	37%	75%	32%	48%	91%	84%	92%	89%
United Kingdom	100%	100%	100%	100%	100%	97%	93%	97%

CONCLUSIONS

This paper presents a novel approach to analyzing operational efficiency of railways. Six models analyze various aspects of micro and macro capacity utilization. The inputs and outputs chosen and the results provide a good picture of the status of railways in each country. New models that are developed by passenger satisfactions as their outputs provide a new horizon for analyzing the quality of capacity utilization. It is concluded that data envelopment analysis provides a powerful tool for analyzing relative operational efficiency of railways.

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