UNIVERSITY OF BIRMINGHAM
University of Birmingham Research at Birmingham

Benchmarking environmental and economic impacts from the HSR networks considering life cycle perspectives

Rungskunroch, Panrawee; Shen, Zuo-Jun ; Kaewunruen, Sakdirat

DOI:
10.1016/j.eiar.2021.106608

License:
Creative Commons: Attribution-NonCommercial-NoDerivs (CC BY-NC-ND)

Document Version
Peer reviewed version

Citation for published version (Harvard):
Rungskunroch, P, Shen, Z-J & Kaewunruen, S 2021, 'Benchmarking environmental and economic impacts from the HSR networks considering life cycle perspectives', *Environmental Impact Assessment Review*, vol. 90, 106608. https://doi.org/10.1016/j.eiar.2021.106608

Link to publication on Research at Birmingham portal

General rights
Unless a licence is specified above, all rights (including copyright and moral rights) in this document are retained by the authors and/or the copyright holders. The express permission of the copyright holder must be obtained for any use of this material other than for purposes permitted by law.

•Users may freely distribute the URL that is used to identify this publication.
•Users may download and/or print one copy of the publication from the University of Birmingham research portal for the purpose of private study or non-commercial research.
•User may use extracts from the document in line with the concept of ‘fair dealing’ under the Copyright, Designs and Patents Act 1988 (?)
•Users may not further distribute the material nor use it for the purposes of commercial gain.

Where a licence is displayed above, please note the terms and conditions of the licence govern your use of this document.

When citing, please reference the published version.

Take down policy
While the University of Birmingham exercises care and attention in making items available there are rare occasions when an item has been uploaded in error or has been deemed to be commercially or otherwise sensitive.

If you believe that this is the case for this document, please contact UBIRA@lists.bham.ac.uk providing details and we will remove access to the work immediately and investigate.

Download date: 03. May. 2024

Benchmarking environmental and economic impacts stemming from the HSR networks considering life cycle perspectives

Panrawee Rungskunroch[1,2,a], Zuo-Jun Shen[2,b], Sakdirat Kaewunruen[1,c*]

[1]School of Engineering, University of Birmingham, Birmingham, B15 2TT, UK

[2]Institution of Transportation Studies, University of California Berkeley, CA 94720, USA

[a]r.panrawee@berkeley.edu, [b]shen@ieor.berkeley.edu, [c]s.kaewunruen@bham.ac.uk

Corresponding author: s.kaewunruen@bham.ac.uk

Abstract

This paper unprecedentedly benchmarks the environmental and economic impacts of notable high speed rail (HSR) networks. The research's goals are to point out the environmental impact (EI) from the HSR networks and evaluate their full life cycle cost (LCC). The emphasis in this study is on five HSR networks to depict the effectiveness of sustainable transport policies in each particular country. Both life cycle assessment (LCA) and LCC models are adopted for a new critical framework capable of benchmarking the lifecycle sustainability of HSR networks. Our findings demonstrate that Chinese network (CR) is the leader in energy saving, consuming only 67.55 GJ/km yearly, and emits the lowest CO_2, at an amount of 77,532.32 tCO_2/km annually. These impressive results stem from key enabling policies related to eco-friendly rolling stock design, sustainable construction, and green energy grids. With respect to the LCC analysis, the French network (SNCF) takes advantage of the economy of scale and achieves the lowest cost among the five networks. It estimates that the SNCF network spends approximately £1,990,599.51 per km annually at a 6% discount rate. The implications of these findings are discussed, finding that the initial project has a high chance of being

successful on economic grounds than the later project, due to the influence of the time value of money.

Keywords: *High-speed rail (HSR), Environmental impact (EI), Economic impacts, Life cycle cost (LCC), Life cycle assessment (LCA)*

Highlights

- Detailed LCA and LCC frameworks for HSR networks in relation to environmental and economic perspectives.
- This is the world first to benchmark both environmental and economic impacts derived from highspeed rail systems globally.
- An analysis of five notable HSR networks that are selected according to different geographic regions, technologies, services and relevant conditions.
- Long-term network life cycle is evaluated by NPV analysis. The life cycles for rolling stock and HSR track are estimated at 35 and 70 years, respectively.
- A sensitivity analysis for LCC is provided using the Monte Carlo Simulation (MCS), which strictly follows the ISO 14040 standard. It is an advantage for rail authorities to control financial plan during uncertainty situations.

1. Introduction

In the past several decades, global warming has become a severe issue that needs a response to reduce CO_2 from all sectors. The transportation sector has shared a quarter of global emissions (UIC, 2017). With the dramatic growth of rail networks, many attempts to reduce emissions have led to the development of new designs for rolling stock, and in construction and operational processes. However, only a few companies show satisfactory outcomes.

One primary problem with CO_2 emissions is that most railway companies have not been thoroughly concerned with emissions throughout the HSR lifecycle. In the manufacturing process, the construction of track and rolling stock has also emitted a high volume of CO_2. This paper aims to environmental impact assessment (EIA) of HSR networks in leading precisely to reduced environmental impact (EI). In addition, it seems that a common problem faced by railway companies is financial issues due to the exceedingly high cost of investment and operations. The research also deals with economic aspects of sustainability along with rail network lifecycle.

In comparison with other studies, the benchmarking method has the advantage that upcoming networks can clearly understand HSR lifecycle and adopt practical strategies from successful rail networks.

2. Background

The construction of HSR track has spread across the world to produce a network of more than 52,000 km (Dindar *et al.*, 2019; UIC, 2020; Sresakoolchai and Kaewunruen, 2020). This development is based on the belief that a HSR service is inevitably essential to expanding their unlimited potential (Korail Sustainability Report, 2018; JR Central, 2019; Alawad and Kaewunruen, 2021). In reality, the rapid expansion of a city may affect the environment, since it can contribute to an increase in global warming, which has led to the average global temperature rising by around 0.8°C (1.4°F) since 2000 (NOAA, 2019). Many organisations have launched campaigns to reduce the sources of global warming; for example, Greenpeace has advocated the substitution of coal, oil and gas with other green and clean forms of energy (Greenpeace, 2019). The UNEP (UN Environmental Programme) is currently involved in global, regional and national projects in seven differently-themed areas, including climate change (UNEP, 2019).

The transportation sector is one of the main contributors of CO_2 in the atmosphere due to the increased demand for transport, resulting in higher energy consumption from oil and other fossil fuel sources. The transportation sector consumes 28.8% of energy and emits 28.3% of the total CO_2 from fuel combustion (IEA, 2017; UIC, 2017; European Commission, 2017; UIC 2016b; Office of the Rail Regulator, 1994). The railway sector has also made efforts to reduce energy use and CO_2 emissions. European railway sectors have planned to cut CO_2 emissions of passenger and freight trains by 50% by 2030 (UIC, 2015). In comparison with other transportation types, HSR could remarkably reduce its EI as it emits the lowest volume of pollutants. Some researchers have found that HSR could reduce environmental pollution by 7.35% in China (Yang *et al.*, 2019). In Japan, the Shinkansen model "N700" emits only 8.34% of the total emissions of an aeroplane (JR Central, 2017). In addition, the UIC report has recorded data from European countries and found that HSR only emits 17 gCO_2 per km, whereas buses, private cars and aeroplanes emit 30, 115 and 153 gCO_2 per km, respectively (UIC, 2017), as shown in Figure 1.

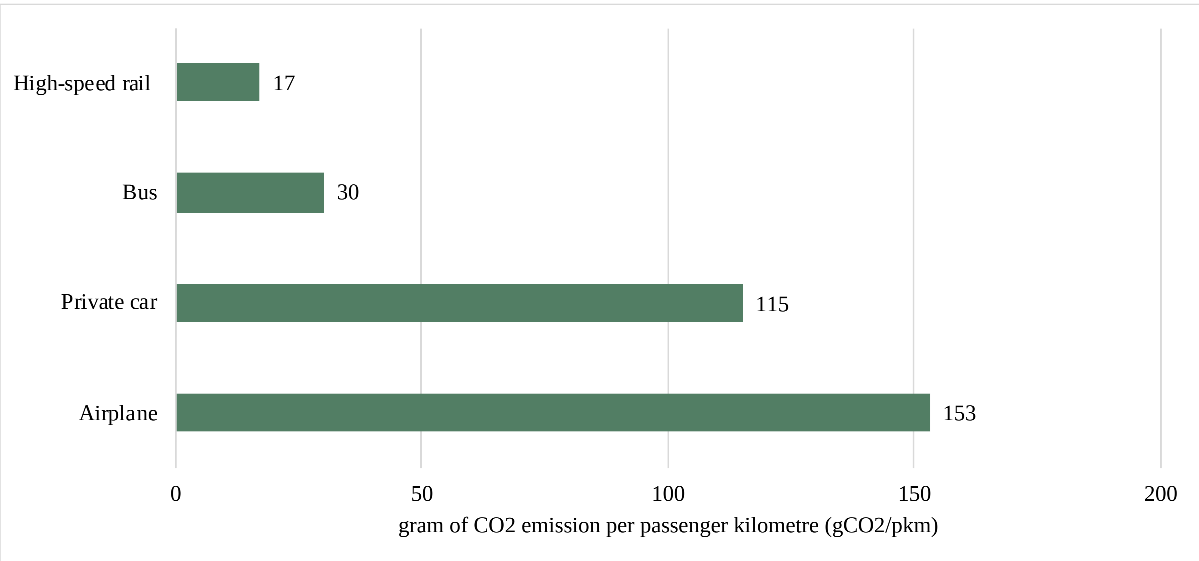

Fig. 1 Comparison of the amount of CO_2 emissions of HSR with other shared mobility and public transportation in EU (UIC, 2017)

Although many researchers have firmly asserted that HSR is beneficial to the environment, economic feasibility must be a concern as HSR operations are very costly. In fact, investment in HSR requires a long-term payback period, and most HSR projects require subsidisation from local government. Therefore, technology replacement in new systems should be addressed in terms of financial status. There are various attempts to sustainably develop HSR networks, including the application of new technologies. Some research has described and compared the railway systems of each country in terms of new technologies, economics and emissions (Merkert, Smith and Nash, 2010; Ibeas *et al.*, 2012; Lin, Qin and Xie, 2020).

By achieving environmental and economic sustainability goals, this research provides life cycle assessment (LCA) and life cycle cost analysis (LCCA) frameworks for HSR networks. To our knowledge, no published papers have addressed benchmarking based on LCA and LCC models across existing HSR networks. As is known, the success of HSR services relies on many factors. This paper clearly states the outcomes for the performance of HSR networks under different technologies, policies and relevant conditions. These outcomes can be integrated into new standards for upcoming HSR projects.

3. Research methodology

Upcoming HSR services can indeed generate uncountable benefits for society, especially in terms of environmental and economic impacts. Several HSR networks have been greatly admired over other types of public transportation and vehicle types. The reason is that HSR networks have the lowest energy consumption and greenhouse gas (GHG) emission per passenger (Wilkerson, 2005; de Rus and Nombela, 2007; Chester and Horvath, 2010).

With respect to the sustainable development goals of HSR networks, environmental and economic analyses are imperative approaches that take into account systematic thinking and whole life aspect of HSR networks’ life cycles. The LCA and LCC models are integrated into this investigation. The LCA analysis aims to define environmental benefits, whereas the LCC analysis focuses on economic perspectives of future HSR projects. Both the LCA and LCC models are calculated for four stages of the HSR network life cycle, namely manufacturing, operation, maintenance and demolition, as shown in Figure 2. The outcomes are expected to provide best practices, enabling stakeholders to adopt sustainable policies for future HSR projects.

The selection of five notable routes involves multiple criteria. Firstly, the network and service should be steady and reliable, which is measured in terms of its long-time operation for at least ten years. With respect to avoiding bias, the chosen HSR routes should be mixed by geographical region, technologies and relevant conditions. Also, these routes can include both successful and unsuccessful networks. The reason is that differentiation across rail networks can be a key driver for wide application in new HSR projects. Based on this study, the chosen routes from five HSR companies are: Tokyo-Osaka from JR Central, Japan; Beijing-Shanghai from China state railway group (CR), China; Seoul-Busan from Korail, Republic of South Korea; Paris-Lyon from SNCF, France; and Madrid-Barcelona from Renfe, Spain.

Table 1: Summary of HSR companies, routes, distance, rolling stock models and weights of rolling stock

Operator	**Route**	**Rolling stock model**	**Weight of rolling stock (tons)**
JR Central	Tokyo-Osaka	N700	715
CR	Beijing-Shanghai	CRH380A	890
Korail	Seoul-Busan	KTX-II	694.4
SNCF	Paris-Lyon	TGV	616
Renfe	Madrid-Barcelona	AVE	850

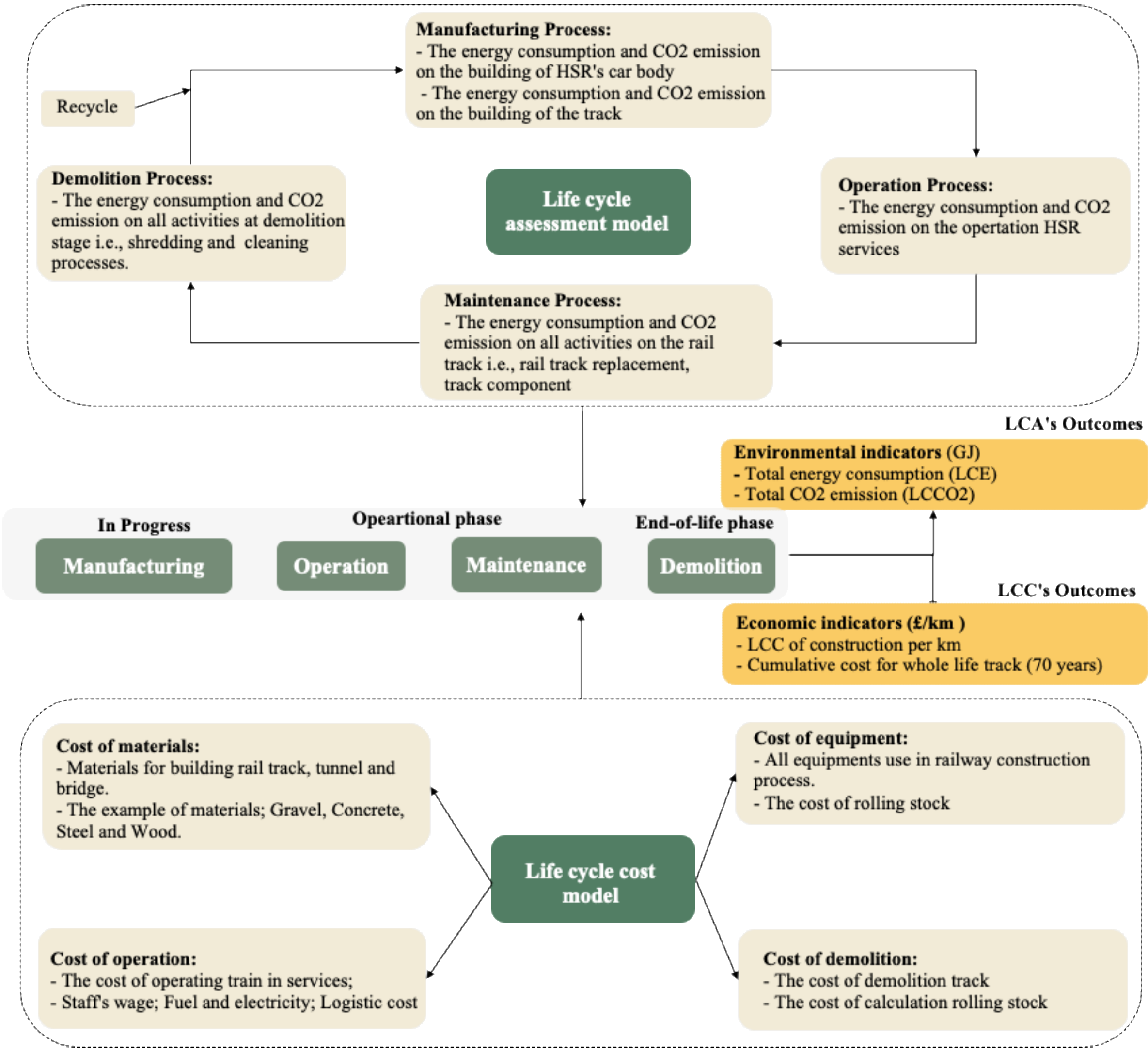

Fig. 2 Overall view of the research framework

4. LCA for HSR networks

One of the key objectives in this study is to assess the EI of the operation of HSR services. The LCA reflects the amounts of energy consumption and CO_2 emissions at each stage of the life cycle. Some researchers have pointed out that LCA analysis results can lead to reductions in the long-term effects on humans and wildlife, improvement in the quality of products, and decreased amounts of GHG emission (Patra, 2007; Banar and Ozdemir, 2015; Kaewunruen *et al*., 2020; Rungskunroch *et al*., 2021a, 2021b, 2021c). As shown in Figure 3, the life cycle of a HSR network contains four stages: (i) the manufacturing, pre-assembly and logistics stage of vehicles and infrastructure; (ii) the operational stage of HSR services; (iii) the maintenance stage of vehicles and infrastructure; and (iv) the demolition stage of the vehicles. Each stage in the life cycle of a railway operation contains various inputs in terms of energy (fuel, electricity), raw materials, outputs of emissions (CO_2, NO_2, CH_4 (Methane)) and other waste. Regarding the outputs, this study discusses and compares only the amount of CO_2 emissions due to this being almost 80% of total outputs (EPA, 2018; FAO, 2014; IPCC, 2014).

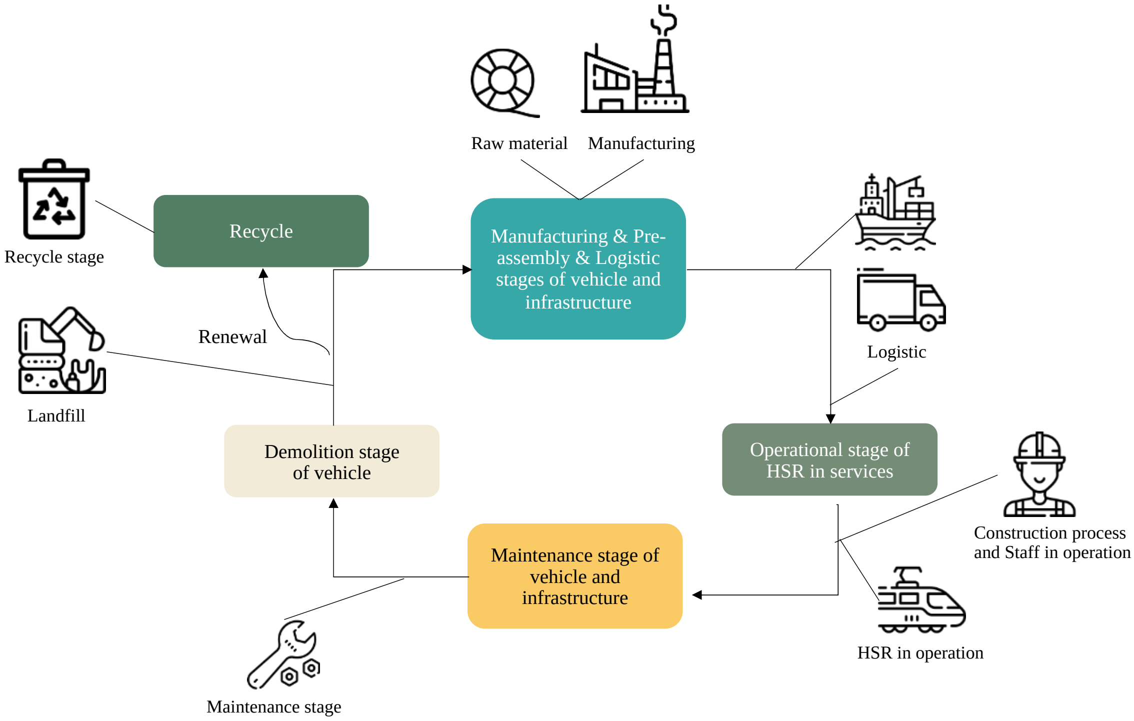

Fig. 3 The life cycle of a HSR network

By evaluating EIs, the calculation of the whole-life energy consumption (LCE) and life cycle of CO_2 ($LCCO_2$) emissions are provided based on the LCA analysis, as shown in equations 1 and 2:

$$LCE = \sum_{i=1}^{n} EC_i \quad (1)$$

$$LCCO_2 = \sum_{i=1}^{n} CE_i \quad (2)$$

where LCE = life cycle of energy consumption; $LCCO_2$ = life cycle of CO_2 emissions; EC_i = total energy consumption (GJ) in stage i; CE_i = total CO_2 emission (t) in stage i; i = {manufacturing and pre-assembly, operation, maintenance, demolition}.

The emphasis of this study is placed on the service provision period of HSR networks. The construction of infrastructure is considered to be an initial investment, which has already been incurred and cannot be recovered (Kaewunruen *et al*., 2020; Rungskunroch et al., 2019). This section determines the materials composing HSR vehicles and rolling stock as part of operations.

4.1 LCA of manufacturing and pre-assembly stage

The data sets for materials and rolling stock weights are taken from the HSR companies' reports. We are especially concerned with exact figures for mass and energy consumption. The calculation of LCE and $LCCO_2$, which is based on services within the 16-carriage rolling stock model, are provided in equations 3 and 4:

$$EC_{manufacturing} = \sum_{k=0}^{n}(E_k \times W_k) \tag{3}$$

$$CE_{manufacturing} = \sum_{k=0}^{n}(C_k \times W_k) \tag{4}$$

where C_k = CO_2 consumption in material k; E_k = Energy consumption in material k; W_k = weight of material k that a vehicle is composed of; k = {set of material components in the rolling stock}.

4.2 LCA of the operational stage

With respect to the calculation of HSR operations, this study assumes that the life cycle of a vehicle is 35 years that is an average lifecycle of rolling stock (ORR, 2020; Vaičiūnas and

Lingaitis, 2008). Also, the total time in service is calculated from one round trip per day, as in equations (5) and (6):

$$EC_{Operation} = \sum_{n=0}^{70} (0.9 \times O_n) \tag{5}$$

$$CE_{Operation} = \sum_{n=0}^{70} (EC_{Operation} \times C_n) \tag{6}$$

where O_n = output energy at year n; n = {0,1,2…,70}; C_n = CO_2 emission from electric power.

By calculating energy consumption as in equation (5), it can be measured from the total output energy multiplied by 0.9, which is an average conversion efficiency from electric power to mechanical energy. This study assumes that the HSR vehicle consists of 16 carriages. This analysis combines the electric power rate at 9,450 KJ/kWh and the CO_2 emission rate at 0.392 x 10^{-3} t/kWh^2 (EPA, 2018; Gao *et al*., 2018; Yousefi *et al*., 2019). Both values are involved in equation (6), which is the calculation of CO_2 emissions in the operational stage.

4.3 LCA of the maintenance stage

The maintenance activities cover both rail infrastructure and vehicles. The maintenance on infrastructure includes a variety of maintenance activities on the rail track, including work on the ballast track, track renewal, and replacement of rails and other track components (Kaewunruen *et al.*, 2016; Pouryousef and et al., 2010). Also, the timeframe for rail track is set at 70 years. On the other hand, the maintenance of vehicles, which have a lifetime of 35 years, is considered during this operation. Replacement of vehicles is therefore set at year 36.

In this section, the LCE and $LCCO_2$ values include track maintenance, vehicle maintenance and staff tools during the maintenance process (machines and cars). From the calculations, the energy consumption of a vehicle with 16 carriages is estimated to be 12,500 kWh/maintenance, while the CO_2 emissions across the two rounds of HSR lifecycle is 190 tons (Miyauchi *et al*., 1999).

4.4 LCA of the demolition stage

The demolition stage is the final stage of a HSR network's life cycle, with end-of-life rolling stock and rail track being destroyed and eliminated at year 35 and year 70 of service, respectively. HSR vehicle bodies mostly contain lightweight materials, like aluminium and alloy, allowing some rolling stock material to be reused and recycled (Kaewunruen *et al*., 2018; Rungskunroch *et al*., 2019). For example, the table and seats are composed with plastic and polymer. The recycle stage is started with cleansing, dying, crushing, and reforming to the new products. Non-recycled components are shredded and sent to landfill such as concrete (Yue, 2013)

Similarly, end-of-life rail infrastructure components contain both recyclable and waste parts. The recyclable parts are transformed for other purposes; for example, steel can be melted and reformed for construction projects. Nevertheless, some components are non-recyclable and contaminated with toxins, such as ballast. This needs to be cleaned and destroyed. With respect to the demolition stage, the calculation of the LCE and $LCCO_2$ values for the whole lifecycle includes demolition of rail infrastructure (track, bridges and tunnels) and two lots of decommissioning of carriages.

5. LCC of HSR networks

On the other hand, life cycle cost analysis (LCCA) is a tool for evaluating the performance of a project, considering especially the budget throughout its entire life cycle. In addition, LCCA is often used to gauge and control the operational conditions that are valuable in order for owners, project managers and stakeholders to understand in detail the viability of the project and the necessary long-term profits (Katpuschenko and Trukhanov, 2018). In practice, LCCA can reveal annual cash flow, payback period, internal rate of return, and future value, which are needed for an organisation to push strategies along with products or services. LCCA is suitable for projects that may have alternative options, so this method is evidently suited for benchmarking net profits.

For railway businesses, LCCA plays an essential role in railway infrastructure management, since the construction of a railway track requires high investment and a longer-term payback period. It is also used as guidance by infrastructure managers to make maintenance decisions (Zoeteman, 2001; Chester and Horvart, 2010). On these grounds, LCCA is adopted in this study in order to benchmark economic impacts based on the time value of money. The life cycle cost (LCC) can be calculated according to equation (7). Also, NPV analysis is used in this study to find the exact life cycle cost, as shown in equation (8).

$$LCC = \sum_{i=1}^{n} C_i \qquad (7)$$

$$NPV = \sum_{k=0}^{n} \frac{A_i}{(1+r)^i} - A_0 \qquad (8)$$

where C_i = total life cycle cost at stage i; i = {manufacturing and pre-assembly, operation, maintenance, demolition}; A_i = cash flow at year i; A_0 = initial investment; r = discount rate; k = time in unit years.

The LCC analysis is calculated based on a period of 70 years, which is the average life cycle of HSR tracks, as shown in Figure 4. In this study, NPV analysis is included for estimating whole life cost, as shown in equation (8). This analysis is based on a standard discount rate of 6%. Moreover, this research gives precedence to electricity cost. This is related to the energy consumption rate calculated in the LCA section above. The energy cost is calculated based on the electricity charges in each country.

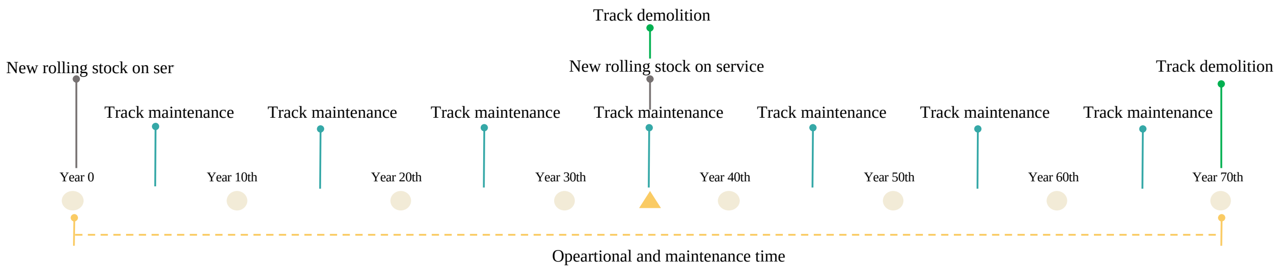

Fig 4: Overall timeline of a HSR operation

5.1 LCC of the manufacturing and pre-assembly stage

The required materials for the construction of rail track are shown in Table 2. There are 11 significant elements that are needed for the construction process, and the data in the table for the costs of materials are collected from reliable sources and using the average market prices. However, differentiation in the price of construction is also due to import taxes in the different countries. Import taxes in European nations are usually higher than in Asian countries; for instance, the import taxes for goods in France are 18.6%, and in Spain 21% (Department for Business, Energy and Industry Strategies, 2019; Global source, 2020). This study also includes 10% of the shipping fee as the initial construction cost.

Table 2: Summary of the costs of material per single km of HSR track (based on electricity costs on 09 December 2020)

Cost of material	**Cost (£/km)**				
	CR	**JR Central**	**Korail**	**SNCF**	**Renfe**
Gravel/Sand	6,459,384.69	7,622,073.9	7,751,261.6	8,306,768.71	8,461,793.94
Concrete	23,389,306.8	2,747,892	117,361.05	444,235.62	688,148.79
Wood	653.25	3,047.8032	1,674.28	6,337.49	9,817.17
Steel	225,277.2	265,827.1	270,332.64	289,706.479	295,113.13
Steel low-alloy	13.32	89.79	152.40	129.22	200.18
Zinc	0	0.09	0.4	0	0
Copper	0	11.23	48.02	0	0
Ceramics	349.86	2927.79	6,438.47	3,394.16	5,257.77
Aluminium	0	0.486	2.079	0	0
PVC	0	0.92	3.94	0	0
Excavation of soil	0	332,351.1	1,421,724.2	0	0
Summary	**30,074,985.12**	**10,974,222**	**9,568,999.1**	**9,050,571.69**	**9,460,330.98**

With respect to equipment for the operational stage, information on the costs of all 11 types of construction equipment that are involved is based on electricity charges in each country. The costs can be split into two types: track and earthwork costs, as shown in Table 3.

Table 3: The costs of construction equipment per single km of HSR track (based on electricity costs on 25 November 2020)

Construction equipment	Track			Earthwork			
	Working time (h)	**Rated power (kW)**	**Total (kwh)**	**Working time**	**Rated power**	**kwh**	**Total (kwh)**
Concrete distributor	45.6	22	1,003.2	-	-	-	1,003.2
Concrete mixing plant	45.6	160	7,296	219.9	160	35,184	42,480
CNC grinding machine	45.6	160	7296	-	-	-	7,296
Gantry crane	113	86.5	9,774.5	-	-	-	9,774.5
Two-way transporter	34.5	110	3,795	-	-	-	3,795
CA mortar truck	27.7	90	2,493	-	-	-	2,493
Track laying machine	6	396	2,376	-	-	-	2,376
Spiral drilling machine	-	-	-	311.2	90	28,008	28,008
Excavator	-	-	-	5,889	125	736,125	736,125
Loading machine	-	-	-	2,944.5	162	477,009	477,009
Concrete pump	-	-	-	439.8	115	50,577	50,577

5.2 LCC of the operational stage

The operational costs include the rolling stock, staff wages, fuel and electricity based on each country's standard price. The number of staff employed is estimated at 50 people/km. As mentioned, HSR network lifecycle is projected to be 70 years; this research uses the first year of each HSR operation based on reality. For instance, the Tokyo-Osaka HSR line has operated since 1964; hence, the LCC calculation is applied from 1964 to 2034. Also, NPV analysis and discount rate are applied with the LCC during that period.

5.3 LCC of the maintenance stage

The maintenance stage LCC mainly involves track and rolling stock upkeep. Track maintenance and track monitoring stages are required during HSR operations to preserve levels of safety. This study assumes that significant track maintenance is carried out every five years.

Maintenance costs include materials and machinery costs, and is estimated to be 15% of initial construction costs.

5.4 LCC of the demolition stage

The demolition stage LCC value includes demolition and logistical costs of using landfill. The recycling rates, which differ by area, are taken into account (EU stat, 2010). The rolling stock end-of-life cost is calculated at the 35^{th} and 70^{th} years, whereas, rail track lifetime runs out at 70^{th} year.

The HSR demolition stage can be separated into two parts: demolition of rail track and demolition of rolling stock. The end-of-life of rail track involves recycled and non-recycled materials, whereas the end-of-life of rolling stock mostly involves aluminium and steel, which are recyclable materials. Non-recyclable parts (i.e. wood, polypropylene and nylon) are sent for shredding and landfill. On the other hand, contaminated products or dangerous substances (i.e. ballast) require a cleaning process to reduce their EI. Therefore, the cost of demolition of these materials is higher than for non-toxic materials. All recycled materials (i.e. steel, concrete and soil) are removed from the rail track and used for others purposes.

6. Results and discussions

With the aim of benchmarking environmental and economic impacts across HSR networks, all LCA outcomes are normalised into single units: 'GJ/km' and 'tCO_2/km', as shown in Table 4. The LCE and $LCCO_2$ fractions at each stage of LCA are illustrated in Table 5; moreover, the average LCE and $LCCO_2$ for each stage are shown in Figure 5.

Table 4: Summary of LCE and $LCCO_2$ results

Life cycle stage	Source	Total LCE				
		CR	JR Central	Korail	SNCF	Renfe
Manufacturing	Rolling stock	150.84	121.18	117.69	104.60	72.03
	Infrastructure	8,493.85	4,091.83	2,440.29	1,538.68	2,336.23
Operation	Whole system	5,554,449.97	4,947,783.22	3,059,415.30	1,977,384.81	4,989,760.67
Maintenance	Rolling stock	567,000.00	283,500.00	226,800.00	226,800.00	340,200.00
	Infrastructure	101,926.18	49,101.97	29,283.45	18,464.13	28,034.79
Demolition	Whole system	360.00	756.00	720.00	720.00	720.00
Total LCE (GJ)		6,232,380.84	5,285,354.20	3,318,776.73	2,225,012.22	5,361,123.72
Total LCE per km (GJ/km)		4,728.53	10,262.09	7,948.30	5,439.25	8,632.53
Annual LCE per km (GJ/km)		67.55	146.60	113.55	77.70	123.32
Life cycle stage	**Source**	**Total $LCCO_2$**				
		CR	**JR central**	**Korail**	**SNCF**	**Renfe**
Manufacturing	Rolling stock	6,486,560,300.00	5,211,113,050.00	5,060,974,688.00	4,489,574,320.00	3,097,514,750.00
	Infrastructure	950,782.00	16,504,870.00	8,599,722.00	6,847,677.00	10,394,851.00
Operation	Whole system	635,665,579.10	566,237,072.20	350,127,377.40	226,297,016.80	571,041,079.80
Maintenance	Rolling stock	18,540,000.00	9,270,000.00	7,416,000.00	7,416,000.00	11,124,000.00
	Infrastructure	11,409,383.24	198,058,444.30	103,196,658.60	82,172,127.86	124,732,622.90
Demolition	Whole system	12,400.00	26,040.00	24,800.00	24,800.00	24,800.00
Total $LCCO_2$ (tCO_2)		7,153,138,444.34	6,001,209,476.50	5,530,339,246.00	4,812,331,941.66	3,814,832,103.70
Total $LCCO_2$ per km (tCO_2/km)		5,427,262.70	11,652,808.65	13,246,291.85	11,766,062.45	6,143,028.89
Annual $LCCO_2$ per km (tCO_2/km)		77,532.32	166,468.70	189,232.74	168,086.61	87,757.56

Table 5: Summary of total LCE and $LCCO_2$ in the LCA for HSR networks

HSR operator	Total LCE (GJ)	The fraction of LCE for the four stages (%)				Total $LCCO_2$ (tons)	The fraction of LCE for the four stages (%)			
		Manufacturing	Operation	Maintenance	Demolition		Manufacturing	Operation	Maintenance	Demolition
CR	6,232,200.84	0.14	89.12	10.73	0.01	7,153,132.24	90.69	8.89	0.42	0.00
JR Central	5,284,976.20	0.08	93.61	6.29	0.01	6,001,196.46	87.11	9.44	3.45	0.00
Korail	3,318,416.73	0.08	92.19	7.72	0.02	5,530,326.85	91.67	6.33	2.00	0.00
SNCF	2,224,652.22	0.07	88.87	11.02	0.03	4,812,319.54	93.44	4.70	1.86	0.00
Renfe	5,360,799.72	0.04	93.07	6.87	0.01	3,814,820.94	81.47	14.97	3.56	0.00

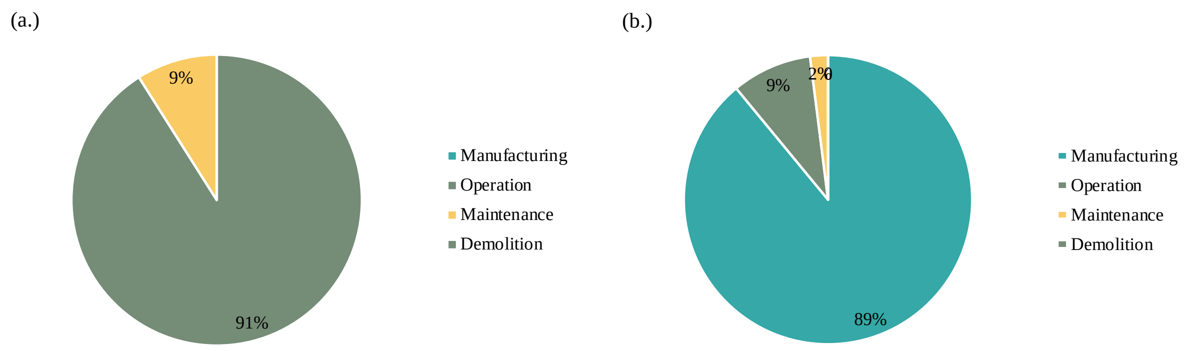

Fig. 5 The average fractions of (a.) LCE and (b.) $LCCO_2$ from HSR LCA stages

Similarly, the LCC results are normalised as '£/km' with Table 6 showing a summary of LCC results that thoroughly represents the whole life cycle stages. Also, these outcomes are applied with a 6% discount rate.

Table 6: Summary of LCC results

Life cycle stage	Details (units)	Total LCC				
		CR	**JR Central**	**Korail**	**SNCF**	**Renfe**
Manufacturing	Track construction costs (material and equipment) (£)	30,086,961.36	11,287,237.70	9,671,069.31	9,267,096.71	9,747,080.34
	Track operational costs (£)	11,976.25	313,015.45	102,070.28	216,525.02	286,749.38
	Total track cost (£/km)	**22,827.74**	**21,916.97**	**23,164.24**	**22,657.94**	**15,695.78**
	Rolling stock year 1 value (£)	2,110,618.95	249,255.43	1,238,051.23	148,168.28	250,679.77
	Rolling stock year 36 value (£)	17,195,744.44	2,030,746.77	10,086,715.33	1,207,164.30	2,042,351.30
	Total rolling stock cost (£/km)	**19,306,363.39**	**2,280,002.20**	**11,324,766.56**	**1,355,332.58**	**2,293,031.07**
Operation	Tariff (£/km)	2,488	11,248	7,328	9,896	7,776
	Bonus (£/km)	99.52	-	290	402.16	300
	Fuel and electricity (£/km)	11,976.25	313,015.44	102,070.25	216,525.03	286,749.36
	Total operational cost (£/km)	**14,564**	**324,263**	**109,688**	**226,823**	**294,825**
Maintenance	Total cost of maintenance (including materials and equipment) (£)	362,053,536.40	135,446,852.30	116,052,831.70	111,205,160.60	116,964,964.10
	Total maintenance cost (£/km)	**51,362.42**	**49,313.17**	**52,119.54**	**50,980.36**	**35,315.51**
Demolition	Track demolition (£)	30,190	606,815	314,367	246,954	374,960
	Rolling stock demolition (£)	44,500	35,750	34,720	30,800	21,250
	Total demolition cost (£/km)	**4,554.12**	**9,105.51**	**79,747.72**	**13,451.09**	**24,955.67**
	Total LCC (£/km)	**19,399,671.67**	**2,684,600.85**	**11,589,486.06**	**1,669,244.97**	**2,663,823.03**

The LCA analysis results demonstrate that the largest portions of LCE and $LCCO_2$ come from the operational and manufacturing stages, respectively. All calculations in this study are based on six limitations: (i) the energy needs for 16-cars carriages and round-trip daily services; (ii) the price of electricity and fuel at the standard rates in each country; (iii) the lifecycle timeframe for infrastructure is 70 years, and for rolling stock is 35 years; (iv) concerns regarding differentiation in track characteristics, including standard track, tunnels and bridges; (v) a discount rate of 6% is applied at all stages of the LCC calculations; (vi) all analyses are adjusted to comparable units such as 'GJ/km' 'tCO_2/km' and '£/km'.

In achieving precise results, the study has taken an exact model of rolling stock into account; for instance, the CRH380A, which is CR's electric train model, has been used in the LCA analysis. Each rolling stock model requires a different amount of input energy, causing production of a different amount of CO_2 emissions. It can be concluded that the different rolling stock models have different environmental effects. Moreover, changing to lightweight materials for HSR components can significantly reduce the energy required and long-term $LCCO_2$ emissions. The comparative outcomes clearly state that the CR has the lowest LCE and $LCCO_2$ values at 4,728.53 GJ/km and 5,427,262.70 tCO_2/km. This study suggests that HSR companies should operate their services with EMU trains and lightweight rolling stock. In addition, the use of renewable and low-emission types of energy are alternative methods to reduce EI.

On the other hand, the LCC analysis has measured the whole life cycle of HSR networks, especially of their infrastructure, as shown in Figure 10. This section offers huge benefits for infrastructure management in terms of making the right decision in supporting maintenance plans and special occasions. The maintenance process has been assumed to repeat every five years, and all costs are calculated at 15% of the initial construction cost. The operational costs are included for every single year, and the budgets have been scaled down in periods without significant maintenance. The results show that all of the selected countries have similar LCC fractions. Up to 45% of the LCC occurs in the maintenance stage, with the rest shared between the other stages. Regarding operational cost, this composes of the standard regional wage rates and electricity costs. The huge disparity between legal wage rates for track construction are shown; for instance, for JR Central this is £11,248 per km, but is £2,488 per km for the CR. Moreover, staff wages are significant in the operational and maintenance stages during the life of a HSR service; in other words, this massive differentiation among compensation rates has a great impact on the LCC analysis.

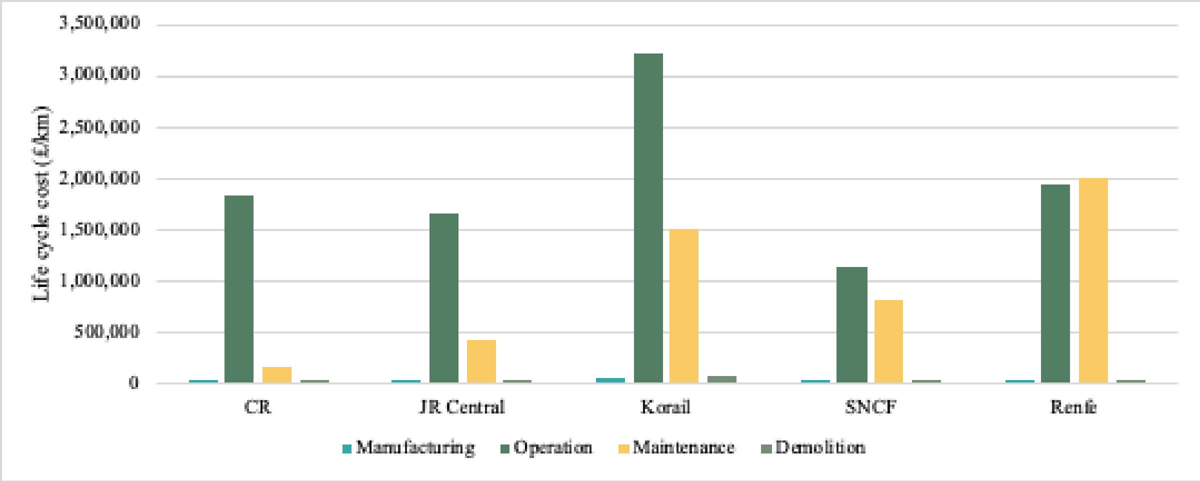

Fig 6. Comparisons of four LCC stages across HSR operators

As a result, the SNCF's LCC shows the smallest value at £1,669,244.97 per km, while Korail's LCC represents the highest value at £11,589,486.06 per km. The SNCF's LCC value is apparently approximately seven times smaller than Korail's. The SNCF network has been continually operated since 1981; i.e., it has been in full service for 23 years longer than Korail's network. Consequently, the LCC of the earlier SNCF project is smaller than the later Korail project due to the impact of the time value of money (TVM). In addition, it is worth discussing these exciting facts revealed by the LCC summary. Earlier HSR projects have a greater chance of achieving economic impacts than later HSR projects.

7. Sensitivity analysis

In section 5, the LCC calculation is estimated and provided based on the actual data collected for regular events. Hence, a sensitivity analysis is required to evaluate irregular situations during operations, such as natural disasters, vandalisms and unexpected damages. One practical advantage of this analysis is that it can be applied to the financial plans of new projects in order to prepare reserve capital.

The ISO 14040 standard has suggested applying the Monte Carlo Simulation (MCS) on the life cycle analysis to reduce uncertainties. The application of MCS on railway research is found in LCA that can reduce uncertainties on recycling process; and the LCC that decrease maintenance and operating costs (Raynolds and et al., 1999; Vandoorne and Gräbe, 2018). This study uses the MCS in the LCC to evaluate uncertainties on unexpected events.

Regarding the MCS, the research takes the triangular distribution with -10% of the standard cost is set as a lower limit, whereas the upper limit is placed at +60% of standard cost. The LCC's standard cost is calculated bases on the normal situation, as shown in Table 6. The study sets the sampling number at 5,000 (n = 5,000). The simulation's outcomes of each rail network are shown in Figure 7-11. The probability density function of the triangular distribution is defined as

$$f(x) = \begin{cases} 0 & x < a \\ \dfrac{2(x-a)}{(b-a)(c-a)} & a \leq x \leq c \\ \dfrac{2(b-x)}{(b-a)(b-c)} & c \leq x \leq b \\ 0 & x > b \end{cases} \tag{9}$$

Where; a is the lower limit, b is the upper limit and c is the mode, where $a \leq c \leq b$

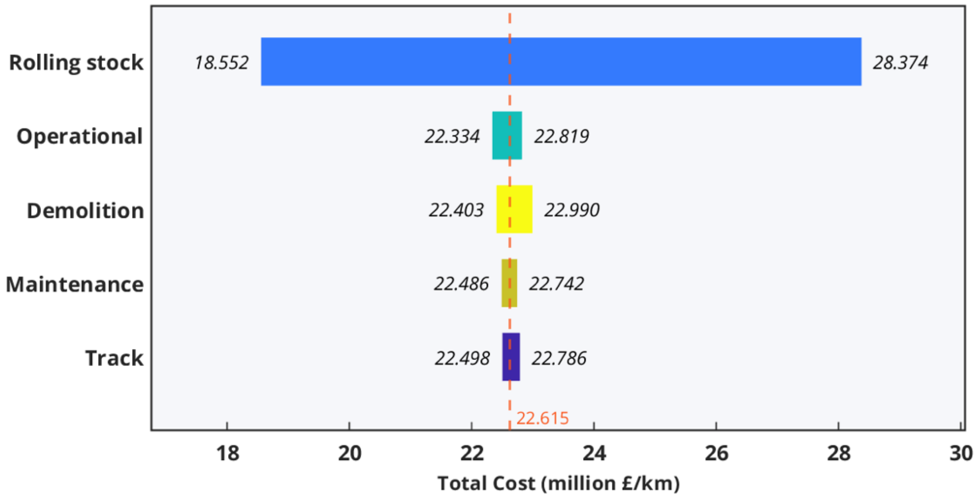

Fig 7. The result of MCS on the CR's network

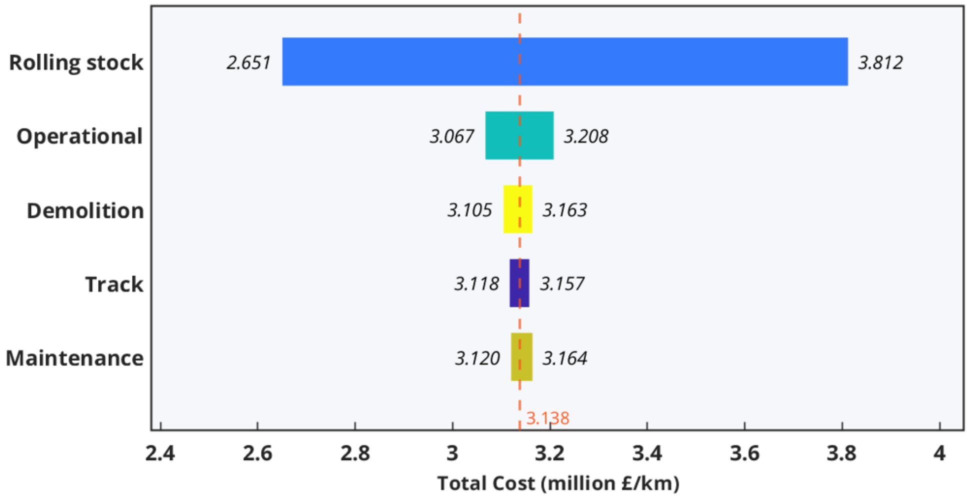

Fig 8. The result of MCS on the JR's network

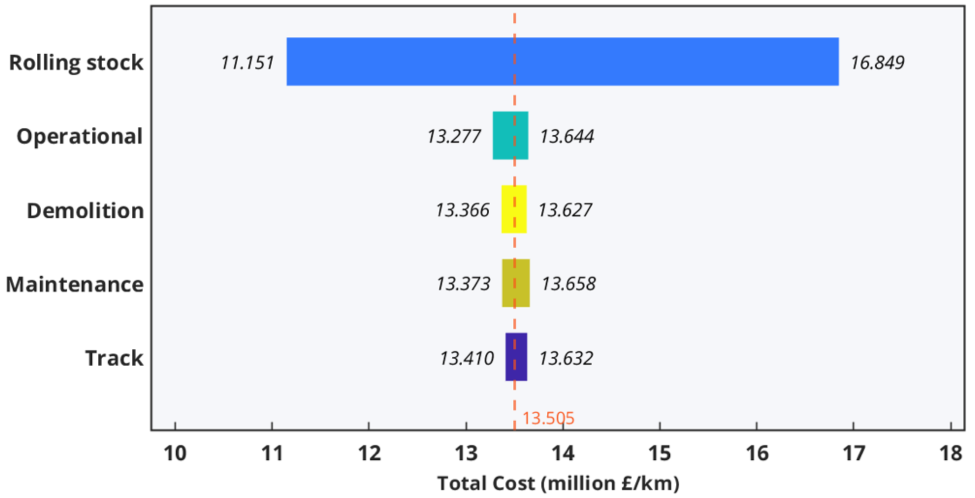

Fig 9. The result of MCS on the Korail's network

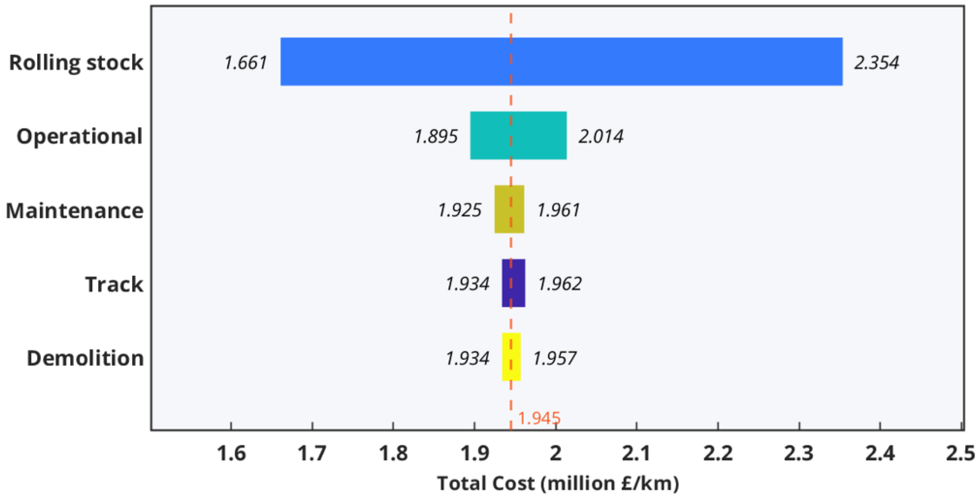

Fig 10. The result of MCS on the SNCF's network

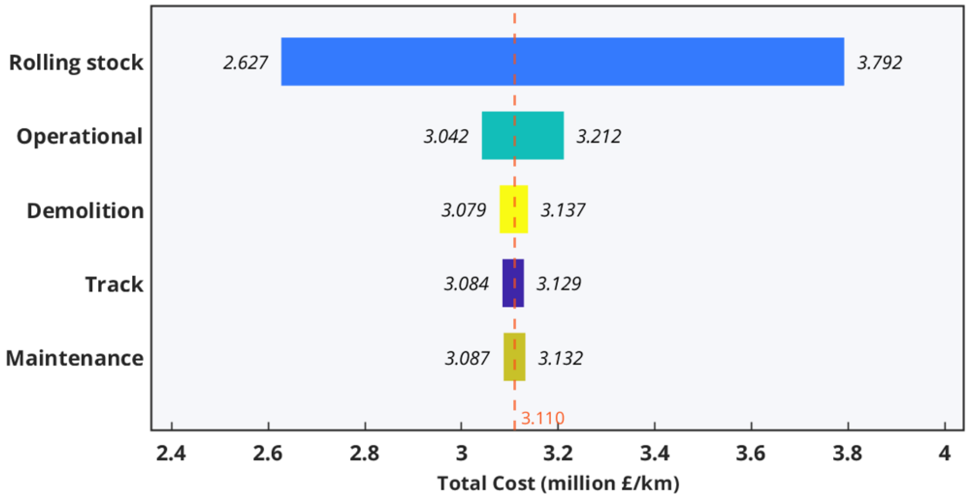

Fig 11. The result of MCS on the RENFE's network

Table 7: The summary of MCS's result of LCC on each rail network

Rail authorities	**Cost (million £/km)**		
	Minimum	**Mode**	**Maximum**
CR	17.56	22.62	30.89
JR	2.46	3.138	4.148
KORAIL	10.51	13.51	18.25
SNCF	1.56	1.95	2.58
RENFE	2.44	3.11	4.11

The MCS's outcomes show the uncertainties on the LCC that can be changed from the normal situation. The research provides five factors related to the LCC, including; rolling stock and track's manufacturing, operational, maintenance and demolition costs. Giving examples, the decreasing of the LCC can come from the replacement of new technologies that lead to saving energy and material costs. In contrast, the increase in LCC occurs from the track's and rolling stock's replacement due to severe damages. As shown in Figure 7 – 11, the rolling stock cost contains the highest uncertainties over other factors, as shown in a high range (Blue bar). On the other hand, the track and maintenance costs have small uncertainties to the whole HSR's life cycle. The results can illustrate that the rolling stock's cost is prohibitive; it also requires replacement after 35 years of its lifetime.

Table 7 illustrates the uncertainties of HSR's LCC in unit' million £ per km'. The CR's network has the highest uncertainties network that shows the LCC in range 17.56 – 30.89 million £/km; while the JR's network has the lowest uncertainties that illustrate the LCC in the range 2.44 – 4.11 million £/km. The earlier network has small uncertainties than the newest network as the time value of money has impacted the LCC.

8. Recommendations and policy implications

The success of HSR projects relies on multiple factors and takes a long time in terms of return on investment. Collectively, our results appear consistent with the idea that there is no outstanding network. Some networks have excellent outcomes on either the environmental or economic perspective. This aspect of this research suggests that upcoming HSR projects should be sustainably developed based on global policies, especially in view of the climate change issue. Moreover, application of both the LCA and LCC analyses is a key driver for HSR projects to achieve their targets. The study also identifies critical developments and recommendations for policymakers as below:

- HSR networks are proudly denoted as the lowest emitter among types of transportation; however, transportation emissions account for 14% of the global total. Endeavours to reduce CO_2 emissions can be stimulated by changing to electric multiple unit trains (EMU), and by using other lower-emission types of energy such as biofuel, hydrogen and other renewable sources. As a result, the value for the operational stage LCE can be reduced, caused by such a significant change in energy requirements over the HSR lifecycle. In terms of sustainable development, seamless connections could encourage travellers to use HSR and public transportation instead of private cars. This shift could directly decrease CO_2 emissions in the long term.

- With respect to investment in HSR networks, these projects require large amounts of money and need a long-term payback period. The analysis results illustrate that most of the LCC is involved in infrastructure construction and maintenance. Therefore, new projects require effective operating plans, which takes reserve capital, activities and maintenance strategies into consideration.
- HSR routes, passenger demand, reasonable pricing and accessibility of networks must be among the top priorities of new projects. High passenger demand can shorten the payback period.
- Regarding the developed countries, the manufacturing cost can be controlled by using its technologies and staff. The rail authorities can reduce both materials cost and buying taxes. Moreover, the majority cost in the operational and maintenance stages can control when the rail operators have proper inspection and treatment schemes.

9. Conclusions

This study aims at benchmarking EI and analysing the total LCC of HSR networks. The outcomes of this research can be adopted into practical strategies for the sustainable development of new HSR projects. The selected networks are considered according to various criteria, i.e., network performance, technologies, geography and services, including; CR, JR Central, Korail, SNCF, and Renfe networks.

In achieving the research aims, the research has been combined with the LCA and LCC analyses. In LCA analysis, the results show that the main LCE fraction occurs in the operational stage, with approximately 91%. Meanwhile, the main $LCCO_2$ fraction is produced in the manufacturing stage, with nearly 88%. The benchmarking of LCE values finds that the CR's HSR network shows the lowest energy used at 67.55 GJ/km annually, and the lowest emissions at 77,532.39 tCO_2/km yearly. Whereas, Renfe's, JR's, SNCF's and Korail's networks emit small amount of CO_2, respectively.

Importantly, our results provide evidence for how to reduce the LCE and $LCCO_2$ values. By shifting to the EMUs, the LCE value for the operational stage can be reduced due to decreased energy consumption. In contrast, the amount of CO_2 emissions could be directly decreased in the rolling stock manufacturing stage. This study recommends that upcoming HSR networks should be developed sustainably in relation to global policies.

Regarding LCC analysis, the NPV analysis is calculated for a time period of 70 years, and the discount rate is 6%. The study assumes that all HSR networks carry out significant maintenance every five years. The results illustrate that the infrastructure stage accounts for most of the LCC, which includes material costs, shipping costs and imported taxes. In conclusion, the total LCC results reveal that the SNCF network shows the lowest values at £1,990,599.51 per km annually, which is early operated since 1982. Moreover, this study provides a sensitivity analysis on the LCC during uncertainty situation by using MCS. The outcomes show that the rolling stock cost contains the highest uncertainties over other costs. Also, the CR's network has the widest uncertainties that can bring the maximum cost at £30.89 million per km. It is worth discussing these interesting facts that the earlier operation network has a significant advantage due to the time value of money.

This aspect of the research suggests that all upcoming HSR networks require sufficient infrastructure construction and maintenance plans in order to cut additional costs for construction activities (i.e. taxes). Also, new projects should combine strategies with their services (i.e. pricing) for profitability due to HSR networks needing a long payback period.

10. Data Availability

The datasets generated during and analysed during the current study are available from the corresponding author upon reasonable request.

11. Acknowledgement

The first author gratefully acknowledges the Royal Thai Government for the PhD scholarship at the University of Birmingham, United Kingdom and the RISEN funding for one year at University of California, Berkeley. The corresponding author acknowledges the Australian Academy of Science (AAS) and the Japan Society for the Promotion of Sciences (JSPS), for the JSPS Invitation Fellowship for Research (Long-term), Grant No. JSPS-L15701, at the Railway Technical Research Institute (RTRI) and the University of Tokyo, Japan. The authors are sincerely grateful to the European Commission for the financial sponsorship of the H2020-RISEN Project No. 691135 "RISEN: Rail Infrastructure Systems Engineering Network", which enables a global research network that tackles the grand challenge of railway infrastructure resilience and advanced sensing in extreme environments (www.risen2rail.eu).

12. Authors' contribution

PR and SK developed the theoretical formalism, performed the analytic calculations. Both P.R. and SK authors contributed to the final version of the manuscript. SK supervised the project during the time of PR study at the University of Birmingham. ZJ managed the project during the time of PR visited at UC Berkeley.

13. Glossary

EMU	Electric multiple unit train
HSR	High-speed rail
kwh	kilo-watt hour
LCA	Life cycle assessment
LCC	Life cycle cost
LCE	Life energy consumption
$LCCO_2$	Life cycle of CO_2
NPV	Net present value
pkm	passenger-kilometre
tkm	tonne-kilometre
TVM	Time value of money

14. References

Alawad H and Kaewunruen S., 2021, 5G Intelligence Underpinning Railway Safety in the COVID-19 Era. Front. Built Environ. 7:639753. doi: 10.3389/fbuil.2021.639753

Banar, M., & Özdemir, A., 2015. An evaluation of railway passenger transport in Turkey using life cycle assessment and life cycle cost methods. Transportation Research Part D: Transport and Environment, 41, 88–105. doi:10.1016/j.trd.2015.09.017

Bilgili, L. *et al.* 2019. Evaluation of railway versus highway emissions using LCA approach between the two cities of Middle Anatolia, *Sustainable Cities and Society*. doi: 10.1016/j.scs.2019.101635.

Borghesi, S., Montini, M. 2016. The best (and worst) of GHG emission trading systems: Comparing the EU ETS with Its follower, Front. Energy Res., 29 July 2016 | https://doi.org/10.3389/fenrg.2016.00027

Chi, Z., Lin, J., Chen, R., Huang, S., 2020. Data-driven approach to study the polygonisation of high-speed railway train wheel-sets using field data of China's HSR train, Measurement Volume 149, January 2020, 107022, doi.org/10.1016/j.measurement.2019.107022

Dahir, A. B., 2019. Uber is working on plans to offer its bus system to Lagos
Available at: https://qz.com/africa/1703725/uber-plans-to-launch-bus-service-in-lagos-nigeria/ (Accessed on 16 May 2020)

Deakin, E., 2010. Environment impact of High-Speed Rail in California Available at: https://gspp.berkeley.edu/assets/uploads/page/HSR10_Deakin.pdf (Accessed on: 26 November 2019)

Department for business, energy and industrial strategies, 2019. Monthly Statistics of Building Material and Components' Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/835264/19-cs10_-_Construction_Building_Materials_-_Commentary_September_2019.pdf (Accessed on: 28 April 2020)

Dindar, D.; Kaewunruen, S.; An, M., Rail accident analysis using large-scale investigations of train derailments on switches and crossings: Comparing the performances of a novel stochastic mathematical prediction and various assumptions, Engineering Failure Analysis. 2019, 103, 203-216. https://doi.org/10.1016/j.engfailanal.2019.04.010

EPA, 2018. Greenhouse Gases Equivalencies Calculator. Available at: https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references (Accessed on: 25 November 2020)

European Commission (EC), 2017. *EU Transport in figures – Statistical Pocketbook 2017*. Publications office of the European Union,

Luxembourg
Eurostat, 2010. Guidance on classification of waste according to EWC-Stat categories. Available at: https://ec.europa.eu/eurostat/documents/342366/351806/Guidance-on-EWCStat-categories-2010.pdf/0e7cd3fc-c05c-47a7-818f-1c2421e55604 (Accessed on 20 July 2020)
FAO (2014). Agriculture, Forestry and Other Land Use Emissions by Sources and Removals by Sinks (PDF). Climate, Energy and Tenure Division, FAO.
Felongco, G. P., 2018. 900 'e-trikes' deployed in Manila. Available at: https://gulfnews.com/world/asia/philippines/900-e-trikes-deployed-in-manila-1.2230670 (Accessed on 16 May 2020)
Gao, M., Cong, J., Xiao, J., He, Q., Li, S., Wang, Y., Yao, Y., Chen, R., Wang, P., 2020. Dynamic modeling and experimental investigation of self-powered sensor nodes for freight rail transport. Applied energy, vol. 257 https://doi.org/10.1016/j.apenergy.2019.113969
Gardner, L., Cruise, R. B., Sok, C. P., Krishnan, K. and Ministro, J. (2007). Life cycle costing of metallic structures. Proceedings of the Institution of Civil Engineers - Engineering Sustainability. 160(4), 167-177
Greenpeace, 2019. 8 reasons why we need to phase out the fossil fuel industry. Available at: https://www.greenpeace.org/usa/research/8-reasons-why-we-need-to-phase-out-the-fossil-fuel-industry/ (Accessed on: 04 December 2019)
Gintautas Bureika, Šarūnas Mikaliūnas. (2008) Research on the compatibility of the calculation methods of rolling-stock brakes. *Transport* 23:4, pages 351-355.
Globalsource, 2020. Products. Available at: https://www.globalsources.com/manufacturers/Concrete-Mixer.html (Accessed on: 28 April 2020)
Harvey, J. *et al.*, 2014. Public attitudes to and perceptions of high speed rail in the UK, *Transport Policy*. doi: 10.1016/j.tranpol.2014.07.008.
Ibeas, ángel *et al.* (2012) 'Modelling transport and real-estate values interactions in urban systems', *Journal of Transport Geography*, 24, pp. 370–382. doi: 10.1016/j.jtrangeo.2012.04.012.
IEA, 2017. *CO_2 Emissions from Fuel Combustion.* Available at: http:// data.iea.org Jiménez (Accessed on: 04 December 2019)
IPCC (2014). *Climate Change 2014: Mitigation of Climate Change*. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
JR Central, 2017. Annual report. Available at: https://global.jr-central.co.jp/en/ (Accessed on: 04 December 2019)
JR Central, 2019. Annual report. Available at: https://global.jr-central.co.jp/en/ (Accessed on: 25 February 2019)
Kaewunruen S, Sussman JM, Matsumoto A. Grand challenges in transportation and transit systems. Front Built Environ 2016; 2(4).
Kaewunruen, S. and Lian, Q., 2019. Digital twin aided sustainability-based lifecycle management for railway turnout systems, Journal of Cleaner Production, Vol. 228, pp. 1537 -1551, doi.org/10.1016/j.jclepro.2019.04.156
Kaewunruen, S., Rungskunroch, P., Jennings, D., 2019. A through-life evaluation of end-of-life rolling stocks considering asset recycling energy recovering, and financial benefit, J. Cleaner Production 212 (2019) 1008-1024 https://doi.org/10.1016/j.jclepro.2018.11.271
Kaewunruen, S.; Sresakoolchai, J.; Peng, J. Life Cycle Cost, Energy and Carbon Assessments of Beijing-Shanghai High-Speed Railway. Sustainability 2020, 12, 206. doi:10.3390/su12010206
Karpuschenko, N. and Trukhanov, P., 2018. Estimation of the life cycle cost of the railway track structure. MATEC Wec of Conferences 216, 01008 (2028), Polytransport System-2018
Korail sustainability report, 2017. Sustainability report. Available at: http://info.korail.com/mbs/english/subview.jsp?id=english_030101000000 (Access on 25 February 2020)
Korail sustainability report, 2018. Second-Party opinion - Korial Green Social and Sustainability Bond. Available at: http://sustainalytics.com/wp-content/uploads/2018/10/Korail-Sustainability-Bond-SPO-FINAL-08292018.pdf (Access on: 25 February 2020)
Lin, Y., Qin, Y. and Xie, Z. (2020) 'Does foreign technology transfer spur domestic innovation? Evidence from the high-speed rail sector in China', *Journal of Comparative Economics*. doi: 10.1016/j.jce.2020.08.004.
Merkert, R., Smith, A. S. J. and Nash, C. A. (2010) 'Benchmarking of train operating firms - A transaction cost efficiency analysis', *Transportation Planning and Technology*, 33(1), pp. 35–53. doi: 10.1080/03081060903429330.

Patra, A. P. 2007. RAMS and LCC in Rail Track Maintenance, Semantic Scholar, Conference proceeding, Corpus ID: 111259063
Pouryousef, H, Teixeira, P, & Sussman, J. "Track Maintenance Scheduling and Its Interactions With Operations: Dedicated and Mixed High-Speed Rail (HSR) Scenarios." *Proceedings of the 2010 Joint Rail Conference*. *2010 Joint Rail Conference, Volume 2*. Urbana, Illinois, USA. April 27–29, 2010. pp. 317-326. ASME. https://doi.org/10.1115/JRC2010-36125
Office of the rail regulator, 1994. Railway operation and the environment guidance, Available at: https://orr.gov.uk/__data/assets/pdf_file/0016/1492/11.pdf (Accessed on: 26 November 2019)
Office of rail road (ORR), 2020. Did you know..? A passenger rolling stock perspective Available at: https://www.orr.gov.uk/search-news/did-you-know-passenger-rolling-stock-perspective-0 (Accessed on: 28 February 2021)
Raynolds, Mario, M. D. Checkel, and R. A. Fraser. "Application of Monte Carlo Analysis to Life Cycle Assessment." *SAE Transactions*108 (1999): 1-9. Accessed February 28, 2021. http://www.jstor.org/stable/44650581.
Rungskunroch, P.; Yang, Y.; Kaewunruen, S. Does High-Speed Rail Influence Urban Dynamics and Land Pricing? Sustainability 2020, 12, 3012. doi:10.3390/su12073012
Rungskunroch, P.; Jack, A.; Kaewunruen, S.; Benchmarking on railway safety performance using Bayesian inference, decision tree and petri-net techniques based on long-term accidental data sets, Reliability Engineering & System Safety 2021a, 213, 107684. https://doi.org/10.1016/j.ress.2021.107684
Rungskunroch, P.; Shen, Z-J.; Kaewunruen, S. Getting it right on the policy prioritisation for rail decarbonisation: evidence from whole-life CO2e emissions of railway systems. Frontiers in Built Environment, 2021b, 7, 638507, doi:10.3389/fbuil.2021.638507
Rungskunroch, P.; Jack, A.; Kaewunruen, S. Socioeconomic Benefits of the Shinkansen Network. Infrastructures 2021c, 6, 68. https://doi.org/10.3390/infrastructures6050068
de Rus, G. and Nombela, G. (2007) 'Is investment in High Speed Rail socially profitable?', *Journal of Transport Economics and Policy*.
Sresakoolchai, J. and Kaewunruen, S., 2020. Comparative studies into public private partnership and traditional investment approaches on The High-Speed Rail Project Linking 3 Airports in Thailand, Transportation Research Interdisciplinary Perspectives 5, 100116. doi: 10.1016/j.trip.2020.100116
UIC, 2015. Rail Transport and Environment – Facts and Figures. Available at: https://uic.org/IMG/pdf/facts_and_figures_2014_v1.0-4.pdf (Accessed on: 26 November 2019)
UIC, 2017. Railway handbook 2017 - Energy consumption and CO_2 emission, UIC, Brussel (Belgium)
UIC, 2020. high-speed. Available at: https://uic.org/passenger/highspeed/ Accessed on 25 February 2020
UN Environment Programme (UNEP), 2019. Climate change. Available at: https://www.unenvironment.org/explore-topics/climate-change (Accessed on 04 December 2019)
Vaičiūnas G. and Lingaitis L. (2008) Investigating the dynamics of passenger rolling stock deterioration, Transport, 23:1, 51-54, DOI: 10.3846/1648-4142.2008.23.51-54
Vandoorne R, Gräbe PJ. Stochastic rail life cycle cost maintenance modelling using Monte Carlo simulation. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*. 2018;232(4):1240-1251. doi:10.1177/0954409717714645
Wilkerson, C. (2005) 'California High Speed Rail Proposal: "High Speed Rail and Wildlife"', in *Proceedings of the 2005 International Conference on Ecology and Transportation*.
World Bank, 2006. Urban transport in developing cities – Challenges, Strategies and Examples. Available at: https://sustainabledevelopment.un.org/content/dsd/susdevtopics/sdt_pdfs/meetings2010/egm0310/presentation_ONeill.pdf (Accessed on: 26 November 2019)
Xu, W. and Huang, Y., 2019. The correlation between HSR construction and economic development – Empirical study of Chinese cities, Transportation Research Part A: Policy and Practic Volume 126, August 2019, Pages 24-36 doi.org/10.1016/j.tra.2019.05.017
Yang, X. *et al.*, 2019. Can high-speed rail reduce environmental pollution? Evidence from China, *Journal of Cleaner Production*. doi: 10.1016/j.jclepro.2019.118135.
Yousefi, A., Guo, H., Biroul, M., Liko, B., 2019.On greenhouse gas emissions and thermal efficiency of natural gas/diesel dual-fuel engine at low load conditions: Coupled effect of injector rail pressure and split injection. Applied energy, Vol.242, pp.216-231 https://doi.org/10.1016/j.apenergy.2019.03.093
Yue, 2013. Life cycle assessment of China's high-speed rail system. Available at: https://pdfs.semanticscholar.org/a001/b778756e6c9b15ec6dd922139b718f446ae7.pdf Accessed on: 20 July 2020

Zoeteman, Arjen., 2020. Life cycle cost analysis for managing rail infrastructure. European Journal of Transport and Infrastructure Research, [S.l.], v. 1, n. 4, sep. 2001. ISSN 1567-7141. Available at: https://journals.open.tudelft.nl/ejtir/article/view/3506. Accessed on: 24 April. 2020. doi: https://doi.org/10.18757/ejtir.2001.1.4.3506