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Sustainability and recyclability of composite materials for railway turnout systems

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Abstract:

To minimize the maintenance frequency as well as the environmental impact caused by the growing number of railway materials reaching the end of their lives, appropriate sustainable management is inevitable prior to either turning them into wastes or leaving them in landfill sites. This paper presents the recent developments of Fibre-reinforced Foamed Urethane (FFU) sleepers installed in the railway turnouts. It determines the recycling and recovering processes of this infrastructure system. The results of recyclability (R_{cyc}) and recoverability (R_{cov}) rates for the railway turnout system are subject to assumptions associated with data which are taken from relevant sources (e.g. UNIFE). The result presents a value of 92.23% and 93.50%, respectively. A sensitivity analysis demonstrates that Mass Recovery Factor (MRF) has superior effect on R_{cyc} and R_{cov} values compared to Energy Recovery Factor (ERF). In addition, this study evaluates environmental life-cycle impacts based on the calculation of carbon emissions and energy consumption over 75 year's lifespan. Comparison of the life-cycle sensitivity for the whole railway turnout system is conducted between FFU sleepers and concrete sleepers. The results show that concrete sleeper emitted almost the same carbon emission as the FFU material, but with much more maintenance and replacement frequency over the mentioned lifespan.

Key words: (Fibre-reinforced Foamed Urethane) FFU; recyclability; recoverability; life-cycle; railway turnouts

Nomenclature

CO₂-e: Carbon dioxide equivalent which includes CO₂; CH₄; N₂O.

EM: Embodied CO₂-e emission (kg)

EE: Embodied energy (MJ)

ERF: Energy Recovery Factor (%)

ECF_k: The embodied CO₂-e emission factor of k material (kg/kg)

EEF_k: The embodied energy factor of k material (kg/kg)

E_i: The quantity of CO₂-e emission from machineries (kg)

F_i: The emission factor of fuel or electricity (g/MJ)

GHGs: Greenhouse gases

LCA: Life cycle assessment

m[P]: Mass of materials which can be taken into account at pre-treatment stage (kg)

m[D]: Mass of materials which can be taken into account at dismantling stage (kg)

m[S]_{SHF}: Mass of materials which are composed of pure ferrous materials like steel and its alloys at shredding stage (kg)

m[S]_{SLF}: Mass of materials which are composed of rubber, fibre, glass etc. at shredding stage (kg)

m[v]: Total mass of all components in railway turnout system (kg)

MRF: Mass Recovery Factor (%)

4Rs: Recyclability rate and recoverability rate (%)

QM_k: The quantity of k material (kg)

Q_iC_i: The quantity of energy consumption (MJ)

R_{cyc}: Recyclability rate of railway turnout by percentage (%)

R_{cov}: Recoverability rate of railway turnout by percentage (%)

Subscript

i: Type of energy (fuel or electricity)

P, D, S: Pretreatment stage, Dismantling stage, Shredding stage.

1. Introduction

With the continuous growth of population, transportation networks will always be a highly demanded industry. They will enable a potential social and economic advancement over the next few decades (Hawkins et al., 2012). In the 21st century, global environmental issues have become a major concern. Global warming, acid rain pollution, and the ozone depletion have led to the extinction of a large number of species. In addition, ecological problems, such as water pollution, desertification and reduced forest cover, are prevalent in developing countries. This makes it urgent for human beings to protect the earth's resources. Meinshausen et al. (2015) reported that over half of the GHG emissions (including land use) in 2014 arise from China (26%), the United States (11%) and Europe (8%); the three biggest contributors. Thus, these countries are responsible for being pioneers to reduce carbon emissions. These environmental challenges of the industrial age have necessitated several international agreements to be signed with the collective aim of limiting the world temperature increases to below 2°C (Damm et al., 2016; UNFCCC, 2016; Yeh et al., 2017; Kaewunruen et al., 2019).

Since the advent of the industrial era, a large number of manufacturing industries have been the main reasons behind environmental pollution. Environmental degradation, resource scarcity, and energy crises have spurred awareness related to environmental protection, as well as, the urgency of improving resource utilization and sustainable development. To date, the advantages of high strength composite materials play an important role in engineering field. However, the environmental problems caused by the high energy consumption of composite materials, waste of materials, and recycling cannot be ignored or underestimated (Sihan, 2013).

Railway turnout is a complex track system, which allows a train to be switched from a specific direction to another (Andersson and Dahlberg, 1998; Kaewunruen, 2014a). Fig. 1 presents a typical railway turnout system that consists of points (switches), check rails, closure rails and crossing, according to its complex geometry. The components of a turnout system include steel rails, tie plate, rubber pads, fasteners, screw spikes, railway sleepers, ballast and sub-ballast (capping layer). Among the variety of components, railway sleepers or bearers play a vital role, which guarantees the stability of the rail gauge and the track system.

Timber, concrete and steel are common materials used in the railway bearers in recent times. Timber has a significant damping coefficient, while concrete and steel can almost negligible (Kaewunruen, 2013). Moreover, it has been proved that concrete has an excellent effect on the stability of track and turnout in lateral, longitudinal and vertical direction (Ferdous and Manalo, 2014; Kaewunruen and Remennikov, 2008). However, timber ages quickly and timber sleepers and bearers tend to last around 10 years or less, making it very expensive for repetitive renewals of a turnout system over a longer term. Recent studies show that steel sleepers have better behaviour in the short term, but sig-

nificant settlement and ballast breakage have been found in railway turnout (Lu and McDowel, 2010; Indraratna et al., 2011).

Fig. 1 A typical turnout system (Kaewunruen et al., 2017)

To date, the usage of new composites materials for railway sleepers has become widespread in the global market, especially the Fibre-reinforced Foamed Urethane (FFU). Composites have demonstrated to be a new material for future generation sleepers and bearers in railway switches and crossings, which is almost maintenance-free and more sustainable from an environmental perspective (Manalo et al., 2010; Kaewunruen, 2014a, 2014b; Ferdous et al., 2015). In many cases in practice, the ad hoc uses of composite materials are required to mitigate the key function of the turnout system such as load resistance, environmental resilience, and stress redistribution. Based on the critical review of open literatures (Ferdous et al., 2015; Kaewunruen et al., 2017), the life cycle assessment with respect to the application of turnout composite bearers has never been investigated. This paper thus provides a quantifiable analysis, which pays much closer attention on material recycling and environmental LCA in railway turnout. This is the first time to evaluate the railway turnouts through the combination of environmental impact and material recycling. Thus, this research will be very beneficial for railway engineers to make decisions by quantifying life cycle performance in railway turnouts. Also, the outcome of this research can provide a valuable reference for choosing environment-friendly materials and achieving sustainable goals.

2. Background on the sustainability of railway turnouts

2.1 Overview of sustainability

There are growing concerns about environmental impacts in choosing sustainable materials in the construction industry. Internationally, the main issue that leads to resource depletion and environmental pollution is the construction industry: superstructures, roads, railways, bridges (Van Erp and McKay, 2013; Kaewunruen et al., 2020). Van Erpa and Rogers, (2008) reported that around 40% of the raw materials and energy produced on Earth are consumed by construction industry, which generates tens of millions of GHGs, air and water pollutants.

Sustainability is a holistic concept that holds economic, social, and environmental factors in a state of balance (Hydes and Creech, 2000). Moreover, it is a complex theory, which is difficult to be defined in a simple term (Zhou and Lowe, 2003). Fig. 2 shows the relationship among social, economic, and environmental factors all combined by sustainability perspective.

Fig. 2 An outline of sustainability (Adames, 2006)

Sustainability can first be perceived as a concept of renewable resources such as forests or fisheries, which subsequently became a widespread slogan for environmental movements (L, 1988). Therefore, a large proportion of proponents think that sustainability supports human life at a specific level in the existing ecological environment and serves the future generations as well (Lele, 1991). In engineering field, sustainability has the

goal of meeting people's or stakeholders' requirements while consuming fewer materials and lesser energy through the whole product life cycle. Recently, there is a growing number of waste materials, which have been produced at the end of life of railway infrastructure systems. Therefore, new composite materials, which have a high R_{cyc} , should be invented and widely utilized.

2.2 Assessment of waste management and life cycle performance

Generally, there are two similar concepts to assess recycling waste in railway industry. Both concepts enable an identical outcome. One is called 4Rs methodology, which calculates the recyclability rate (R_{cyc}) and recoverability rate (R_{cov}) to evaluate end-of-life performance. Another is the environmental LCA methodology, which covers a diversity of assessment methods that can calculate the lifecycle performance in a quantifiable way. This is a technique used to evaluate the environmental performance associated with a product through its whole life cycle (BSI, 2006) for both the whole system and partial components, which focuses on the energy, resources recycling, and emission of products from cradle to grave. Both methodologies provide plentiful benefits across the environment in terms of converting wastes into new products. They both have great research significance for waste management and low carbon construction.

2.2.1 Recycling and recovering processes

Recycling is the process of converting or processing waste materials into usable material (Bowyer et al., 2015; Amini et al., 2007; Dauguet et al., 2015). In addition, recovering refers to the generation of new energies by transferring old equipment or materials into energy forms (Kaewunruen et al., 2019). Moreover, recovering also refers to the waste recovering process, aimed at recovering materials mainly in the form of thermal energy (Haddad et al., 2014; Serrano et al., 2017). Both recycling and recovering processes aim to improve the use-value and lifetime of materials, while reducing environmental impacts by recycling waste materials. The illustration in Fig. 3 presents the waste hierarchy in the UK. The key proposal of the strategy is based on efforts to reduce, re-use, recycle waste, and recover energy from waste (Waste Strategy for England, 2007).

Fig. 3 The waste hierarchy (Waste Strategy for England, 2007)

With regards to the measurement of the performance of recycling process, R_{cyc} and R_{cov} are often referred to in a number of standardization sources. For instance, ISO22628:2002 (2003) and UNIFE (2013) indicate those data for all components of rolling stocks. Although there are no existing data sources for railway turnouts, it also can be a guideline to calculate R_{cyc} and R_{cov} by reasonable modification. As found in the literature review, by Vandermenlen et al. (2003), the Possible Material Recycling (PMR) coming from trains was used to evaluate the environmental performance. Furthermore, (Delogu et al., 2016; Kaewunruen et al., 2019) focused on determinations of R_{cyc} and R_{cov} of rolling stocks through its lifespan. Recently, there is a growing number of wastes, which have been produced at the end of life of railway infrastructure components. Thus, it is necessary to determine R_{cyc} and R_{cov} for railway turnout systems.

2.2.2 Environmental LCA

The life cycle model of railway turnout can be defined by several stages, from design and planning, manufacturing, construction, operations and maintenance and the end-of-life management in railway sector. The goal in this study is to assess the environmental impacts associated with a typical railway turnout system.

Kiani et al. (2008) and Lee et al. (2016) are examples of scholars who have laid emphasis on the calculations of GHG emissions from cradle to grave for railway infrastructures. Moreover, Kaewunruen and Lian (2019) conducted an analysis of life cycle for a railway turnout based on establishing Six-Dimensional building information modelling. It is well known that CO_2 , CH_4 and N_2O are the most dominated GHGs. Significantly, CO_2 was the leading GHGs that results in global warming (Howard et al., 1999; Rawlinson and Weight, 2007). For the purpose of demonstrating the performance of en-

vironmental impacts, these GHGs are denoted as CO₂-e, which was defined by DOE (2014). In this study, energy consumption and CO₂-e are derived as indicators to evaluate environmental impacts quantifiably. The principles of assessment are based on ISO 14040 (2006). In this study, the function of the railway turnout is to provide the flexibility to railway systems by enabling the movements of trains. Its performance characteristics are to support the load distribution and to secure adjacent components of the turnout. The key functional unit of the turnout system and its components is to assure that consistent stress level through the trackbed can be achieved through the applications of resources, with a special attention to turnout bearer materials. According to LCA ISO 14040 (2006), the function of the turnout bearers is to provide load resistance to the crossings. The functional unit is 250:10.5 crossing rate for 21-tonne axle load (RailCorp, 2017). This implies that, with the application of different bearer materials, the cross section of trackbed (depth of ballast) will be slightly modified (<5%) to assure the consistent stress redistribution.

2.3 Main components

2.3.1 Steel

Steel is one of the most important materials within the railway system. It is mainly used in rails and fastening systems in the railway industry. Furthermore, steel is one of the materials, which has the highest recycling rate. If it does not significantly lose its characteristics, steel can be recycled for making new products over and over again (Silva and Kaewunruen, 2017; World Steel Association, 2016; Bowyer et al., 2015; ISO 22628:2002, 2003). Ideally, it is reported that steel has an MRF at 98% with 2% residue (UNIFE, 2013). However, it is also reported that steel presents a 4% gap of MRF. The reason is that UNIFE method has been defined as a possible evolution based on ISO 22628 standard. In reality, only 85% of steel is recycled by steel industry (IISI, 2002; Kiani et al., 2008), and this value is expected to increase to 90% in 2050 (Björkman and Samuelsson, 2014). The loss of metal elements occurs mainly due to materials quality and poor techniques.

2.3.2 Polymers and composites

It is well known that most polymers have similar properties as plastics, which take a long time to degrade, and it is difficult to reduce the waste at the end of its life. However, a Japanese company called SEKISUI produced a composite material called FFU. To date,

it is widely applied in turnout, open steel girder structure, and tunnels over 1300 kilometres (approximately 2 million sleepers) of track (Koller, 2015). It is important to note that there is no standard of recyclability data for a railway turnout. Furthermore, it is reported that FFU has an up to 100% recycling content (RailEngineering, 2016). However, for this value to be truly practical, more studies are required. In addition, rubber is also a widely used material in rail pads, which provide a better hardness and compressive modulus (Pattamaprom et al., 2005).

2.3.3 Aggregates

Railway ballast and sub-ballast are used to construct the foundation of railway tracks for carrying and distributing loads. Aggregates, as the majority of materials in railway turnout, play a decisive role in affecting the R_{cyc} and R_{cov} . It has been shown that construction aggregates have a 93% recycled content (WRAP, 2008). Also, Indraratna et al. (2005) indicated that around 90% of aggregates could be recycled. The other 10% consists of cemented materials. Having experienced cyclic loading of heavy trains, the ballast and sub-ballast particles gradually break and deteriorate. Hence, the phenomenon of ballast volume and porosity decrease occurs because the crushed fine particles migrate within the ballast bed and fill the voids between nearby aggregates (Indraratna et al., 2005). The impurities (sleeper fragments and other sundries) result in wastes.

3 Methodology

3.1 Calculation of R_{cyc} and R_{cov} for a railway turnout system

The evaluation of end-of-life management is based on waste recycling and recovering process. As shown in Fig. 4, there are three stages followed when analysing recycling process of railway turnout: the pre-treatment stage; dismantling stage; and shredding stage. The pre-treatment step aims to extract toxic and explosive substances. At the dismantling stage, materials that can be reused and recycled are individually removed from railway turnout. A large amount of components addressed in this stage due to aggregates are the dominant materials in the railway turnout. Moreover, materials cannot be considered as reusable when they are shredded. Shredder materials can be used to classify into two types: Shredder Heavy Fraction (SHF) and Shredder Light Fraction (UNIFE, 2003; Delogu et al., 2017). In a railway turnout system, the SHF mainly involves metal material (e.g. from steel baseplates, crossing nose, etc.), but the SLF (e.g. from fastening clips, elastomeric pads, etc.) may be sent to recovering process such as fibre and rubber,

which are distributed in the FFU sleepers/bearers and rail pads. Statistically, although about two-thirds of total mass of SLF can be identified as recoverable materials (Krinke et al., 2006), most of the shredding residue is still used for landfill (Cossu et al., 2014).

Fig. 4 The schematic diagram for managing the end-of-life railway turnout through reuse, recycling and energy recovery

The calculation of R_{cyc} and R_{cov} is a complex process due to the lack of sufficient standards for a railway turnout. Additionally, when it comes to the use of new composite materials like FFU in the recent two decades, it is impossible to give an accurate recycling process because of inadequate data and statistics. It was assumed that the FFU has an MRF at 66.7% with 33.3% ERF (Koller, 2015; Sekisui; 2019). Moreover, the MRF for ballast and sub-ballast has been assumed to be 93%. The method has been adopted from UNIFE (2003), which is used to calculate the R_{cyc} and R_{cov} of rolling stocks based on the mass of materials recovered during the pre-treatment, dismantling, and shredding stage. Due to the similarity of material recovering process in railway turnouts, following relations (3.1; 3.2) are derived based on the method:

$$R_{cyc} = \frac{\sum(m[P]_k * MRF_{Pk} + m[D]_k * MRF_{Dk} + m[S]_{SHF} * MRF_{SHF} + m[S]_{SLF} * MRF_{SLF})}{m_v} * 100\% \quad (3.1)$$

$$R_{cov} = R_{cyc} + \frac{\sum(m[P]_k * ERF_{Pk} + m[D]_k * ERF_{Dk} + m[S]_{SHF} * ERF_{SHF} + m[S]_{SLF} * ERF_{SLF})}{m_v} * 100\% \quad (3.2)$$

3.2 Assessment of environmental impacts

The purpose of this study is to estimate the energy consumption and CO₂-e emissions during railway turnout lifespan. The evaluation has been based on integrated lifespan from material manufacturing to the end of demolition stage, which determines the life cycle CO₂-e emission and energy consumption that are subject to assumptions associated with energy consumption and emission data. Krezo et al. (2016) studied the calculation of GHGs from materials as well as fuel and electricity consumption. Similarity, general equations for evaluation of CO₂-e associated with these three main aspects can be express as shown in equations (3.3) - (3.5) below:

$$EM = \sum_{k=1}^N ECF_k QM_k \quad (3.3) \text{ (Krezo et al., 2016)}$$

$$E_{ij} = Q_i C_i F_{ij} \quad (3.4) \text{ (Krezo et al., 2016)}$$

$$EE = \sum_{k=1}^N EEF_k QM_k \quad (3.5)$$

In this analysis, the assessment has been based on integrated lifecycle, which is considered from manufacturing to end-of-life recycling process. It is assumed that materials' replacement stays the same as original during reconstruction. Thus, initial earthwork excavation has not been considered. Fuel and electricity are two main sources considered as energy expenditure. This study does not include investigation consumption and labour requirements before carrying out this construction project. Moreover, due to the various uncertainties in the operation and maintenance stage, known activities are considered.

3.2.1 Calculation of GHG emission

During the process of turnout life cycle, embodied emission is the dominant source of greenhouse gas emission. Furthermore, energy consumption also results in GHG emission; especially, the electricity consumption and fuel consumption. Table 3.1 presents the

emissions factors associated with electricity and fuel consumption, which makes it possible to calculate the quantities of CO₂-e emission with a given unit of source of energy. The embodied factors are listed based on (ICE Database, 2011). Moreover, Krezo et al. (2016) summarized the embodied CO₂-e factors of materials in the railway industry. However, materials like FFU are not on the list of the database. The reasonable assumption is taken before carrying out this study. Table 3.2 provides a summary of embodied CO₂-e and energy factors in railway infrastructures.

Table 3.1-Emission ratio for electricity and fuel consumption (Howard et al., 1999)

Single source	CO ₂ -e to air per unit(g/MJ)	Delivered energy ratio in the UK	Emissions(g/MJ)*
Electricity consumption (MJ)	58.32	3.083	165.93
Fuel consumption (MJ)	81.75	1.110	90.74

*Emissions shows the amount of CO₂-e emitting per primary energy.

Table 3.2-Embodied CO₂-e and energy factors

Components (Materials)	ECF (kg/kg)	EEF (MJ/kg)	[Ref.]
Rail (Steel)	2.78	20	(Krezo et., 2016)
Sleeper (FFU) / (Concrete)	4.26 / 0.277	101.50 / 2.33	(ICE Database, 2011)
Rail pad (Rubber)	2.85	91.00	(ICE Database, 2011)
Fastening system (Steel)	2.78	20	(Krezo et., 2016)
Rail joints (Steel)	2.78	20	(Krezo et., 2016)
Ballast (Aggregates)	0.0052	0.083	(ICE Database, 2011)
Sub-ballast (Aggregates)	0.0051	0.081	(ICE Database, 2011)

3.2.2 Calculation of energy consumption

Throughout the life cycle of a railway crossing, diverse machineries are used in the turnout system. Thus, energy has been consumed for several activities during construction, maintenance, and demolition. Examples of this consumption include fuel consumption including rail laying, ballast spreading and cleaning, sleeper laying, and other such activities. Moreover, due to complex components manufacturing process, electricity consumption has also been taken into account in this study, which would be discussed in Section 4.

In summary, after calculations of the CO₂-e emission and energy for each activity are completed, a total amount of CO₂-e emission and energy consumption can be obtained. Sensitivity analysis can then be conducted to identify the key impactful parameters, including the type of materials, the life span of infrastructure usages, and materials parameters.

Technical drawing of a railway track cross-section. The drawing shows a cross-section of the track bed, including the sub-ballast and ballast layers. The dimensions are as follows:

- Sub-ballast:** The base layer, shown in grey. It has a total width of 4300 mm on each side of the track centerline. The top surface is sloped with a 1.5:1 ratio.
- Ballast:** The layer above the sub-ballast, shown in a lighter grey. It has a total width of 4300 mm on each side of the track centerline. The top surface is sloped with a 1.5:1 ratio.
- FFU sleeper:** The central component, shown in white. It has a width of 1435 mm. The distance from the centerline to the edge of the sleeper is 400 mm.
- Shoulder distance:** The distance from the centerline to the edge of the sub-ballast layer, which is 4300 mm on each side.
- Track Bed Height:** The total height of the track bed is 270 mm. The height of the ballast layer is 180 mm, and the height of the sub-ballast layer is 90 mm.
- Track Bed Slope:** The top surface of the track bed is sloped with a 1.5:1 ratio.

Table 4.1-Material quantities of turnout components

Components	Materials	Quantities	Unit weight	Total weight(kg)	Sources
Rails	Steel	136.361m	60 kg/m	8181.66	(AGICO GROUP, 2019)
Sleeper	FFU	7.463m ³	740 kg/m ³	5522.63	(SEKISUI, 2019)
Rail pad	Rubber	204541.5cm ³	0.95 kg/m ³	194.31	(AGICO GROUP, 2019)
Fastening system	Clips(steel)	272pieces	0.43 kg/pieces	116.96	(AGICO GROUP, 2019)
	Bolts(steel)	544pieces	0.478 kg/pieces	260.32	(AGICO GROUP, 2019)
	Tie plates(steel)	136pieces	9.45 kg/pieces	1285.2	(AGICO GROUP, 2019)
Rail joints	Joints(steel)	8 pieces	20.315 kg/pieces	162.52	(AGICO GROUP, 2019)
	Bolts(steel)	32pieces	0.5kg/pieces	16	(AGICO GROUP, 2019)
Ballast	Aggregates	29.050m ³	1400kg/m ³	40669.34	(Transport Asset Authority.2018)
Sub-ballast	Aggregates	43.199m ³	20kN/m ³	88100.61	(Transport for NSW.2008)

Fig. 6 Materials composition of turnout system

Table 4.2-Mass allocation to end-of-life treatment step and recover factors

Components	Type of material	Total weight(kg)	Allocation to end-of-life treatment steps		Recovery factor (%)	
			[% of mass]		MRF	ERF
Rails	Steel	8181.7	m _D (Dismantling)	0	98	0
			m _{SHF} (Ferrous Fraction)	100	98	0
Sleepers	FFU	5522.6	m _D (Dismantling)	95	66.7	33.3
			m _{SLF} (non-Ferrous Fraction)	5	14.0	19.0
Fastening system	Steel	1662.2	m _D (Dismantling)	0	98	0
			m _{SHF} (Ferrous Fraction)	100	98	0
Rails joints	Steel	194.3	m _D (Dismantling)	0	98	0
			m _{SHF} (Ferrous Fraction)	100	98	0
Rail pad	Rubber	178.5	m _D (Dismantling)	100	80	20
			m _{SLF} (non-Ferrous Fraction)	0	14	19
Ballast	Aggregates	40669.3	m _D (Dismantling)	100	93	0
			m _{SLF} (non-Ferrous Fraction)	0	14	19
Sub-ballast	Aggregates	88100.6	m _D (Dismantling)	100	93	0
			m _{SLF} (non-Ferrous Fraction)	0	14	19

Table 4.3-The results of R_{cyc} and R_{cov}

Recyclability/Recoverability Rates (% in mass)			
Components reuse	Materials recycling	Energy recovering	Waste landfilling
82.87	9.36	1.27	6.50
R_{cyc}			
92.23			
R_{cov}			
93.50			
Total			
100			

This section is aimed at analysing R_{cyc} and R_{cov} to achieve sustainable design and environment-friendly goals. The assumption of material information and mass of allocation to end-of-life treatment step are presented in Table 4.2, which summarizes the results of general material information of each component. It is found, for instance, that all the materials are classified into dismantling stage and shredding stage. The reason for the difference is that material diversity has been limited compared to rolling stocks. It can be noticed that steel cannot be recycled as an energy resource. Nevertheless, the calculation results of R_{cyc} and R_{cov} are 92.23%, 93.50% respectively. Table 4.3 reports a similar value at approximately 95% in case of the combined recycling and recovery rate for rolling stocks (Silva and Keawunruen, 2017). It can be inferred that the similarity of the material types largely affects the R_{cov}. In spite of its distinct mechanical properties, most of the ballast and sub-ballast particles can maintain higher workability after repeated uses. Thus,

a large amount of material can be taken into account as a reuse resource. Moreover, only 6.50% of materials cannot be recovered, which has been considered as waste and lead to landfill.

4.2 Influential factors on recyclability and recoverability

As mentioned in section 4.1, the MRF and ERF are two basic factors taken from (UNIFE, 2013), which have a decisive influence on the R_{cyc} and R_{cov} . Delogu et al., (2016) and Kaewunruen et al. (2018) conducted the sensitivity analysis with the aim of exploring the components of each that have a direct effect on both values. Thus, a sensitivity analysis of MRF and ERF is also taken in this section. The principle is that these two amounts are not specific rates in reality, which means such hypothesis on MRF and ERF have some fluctuation compared to the specific value used in this study.

In order to calculate the most realistic R_{cyc} and R_{cov} , a difference at $\pm 5\%$ changing rate has been applied into individual materials. Fig. 7 and Fig. 8 summarise how MRF and ERF can affect both values, respectively. This is initially shown in Fig. 8, which indicates the results of R_{cyc} and R_{cov} with converting MRF within the range $\pm 5\%$. A steady increase occurred in R_{cyc} from 87% to 97% after converting the value of MRF in a region of $\pm 5\%$ according to this column chart. Similarly, there is an upwards trend which can be identified in R_{cov} , which is a little higher than R_{cyc} . The reason is that the energy recovery resource results in the gap between R_{cyc} and R_{cov} . On the other hand, by contrast, with differences in the ERF value, the R_{cyc} and R_{cov} keep constant at approximately 92.2%, 93.5% respectively (see Fig. 8). This is primarily due to the fact that very few materials can be recovered as an energy resource. Thus, in conclusion, the sensitivity analysis shows improving the MRF of material is a more efficient way to increase the R_{cyc} and R_{cov} . Therefore, recycling technology should be improved to enhance recycle efficiency according to this sensitivity analysis.

Fig. 7 Sensitivity analysis of MRF rate of railway turnout components

Fig. 8 Sensitivity analysis of ERF rate of railway turnout components

4.3 Calculation of GHGs and energy consumption

In this section, the results of assessment are summarized in two parts, one is the carbon emission ($\text{CO}_2\text{-e}$) measured in kilograms (kg), and another is the energy consumption

measured in megajoules (MJ). Based on the presence of CO₂-e, which can be classified into three forms: material consumption; machinery consumption; and electricity consumption. Additionally, electricity consumption and fuel consumption from machines result in total energy consumption. This study has quantified the comparison of FFU sleepers and concrete sleepers associated with CO₂-e consumption and energy consumption over a 75-year lifespan.

4.3.1 Assessment of CO₂-e and energy consumption in different stages

Fig. 9 Life cycle inventory analysis stage of railway turnout

Fig. 9 presents a typical life cycle inventory analysis stage of a railway turnout. It begins with materials manufacturing stage, which involves all of the components like sleepers and fastenings would be produced in a factory. This is followed by the construction and installation stage, which mainly includes the construction of the ballast and installation of all components. After that, this railway system can operate as an asset in operating and maintenance stage. The final stage is the demolition, which denotes recycling, reuse and landfill.

Energy consumption is often accompanied by GHG emissions. With uncertainty for the assessment of energy consumption, reasonable assumptions were applied to this study, which assumes full combustion of fuel and no residue left. Based on the resource from the railway project, Table 4.4 illustrated the machines and their utility numbers estimated in the railway turnout (Kaewunruen et al, 2015; Krezo et al.,2016). Therefore, the usage and assumptions of machinery energy consumptions using FFU sleepers and concrete

sleepers in different stages can be determined (see Tables 4.5-4.8). Those data are estimate based on Kiani et al. (2008), Krezo et al. (2016), and Kaewunruen and Lian, 2019). However, it is important to take into account the operation and maintenance stage (see Table 4.7). Ballast cleaning and replacement has been assumed to be activities within the renewal project. Moreover, ballast resurfacing and rail head grinding are set at 4-year interval and 1-year interval, respectively.

Table 4.4-Machines and their numbers used in turnout lifespan (Kaewunruen et al, 2015)

Items	Components manufacturing	Construction& Installation	Operation& Maintenance	Demolition
Front End Loaders		2	1	1
16t Excavator		2		1
5t Excavator		1		1
Drott		1		1
15t Dump Truck		1		2
5t Dump Truck		1		2
Smooth Drum Roller		1		
Plant Facilities	1			
Desec (Turnout Transporter)	1			
Tamper		1	1	
Regulator		1	1	
Remote Control Facilities			1	
Cutting Machine				1
Road Transportation	1			

Table 4.5-Energy consumption in Components Manufacturing stage

Activity or equipment	Turnout with FFU sleepers		Turnout with Concrete sleepers	
	Fuel	Electricity	Fuel	Electricity
	consumption(liters)	consumption (MJ)	consumption(liters)	consumption (MJ)
Components manufacturing	N/A	2400	N/A	7200

Table 4.6-Energy consumption in Construction & Installation stage

Activity or equipment	Turnout with FFU sleepers		Turnout with Concrete sleepers	
	Fuel	Electricity	Fuel	Electricity
	consumption (liters)	consumption (MJ)	consumption (liters)	consumption (MJ)
Sleeper laying machine	10	N/A	10	N/A
Turnout construction	300	N/A	300	N/A
Ballast transportation/spreading	200	N/A	250	N/A
Sub-ballast transportation/spreading	220	N/A	250	N/A
Tamping machine	30	N/A	30	N/A

Table 4.7-Energy consumption in Operation & Maintenance stage

Activity or equipment	Turnout with FFU sleepers		Turnout with Concrete sleepers		Interval years
	Fuel	Electricity	Fuel	Electricity	
	consumption (liters)	consumption (MJ)	consumption (liters)	consumption (MJ)	
Track reconstruction	With renewal	N/A	With renewal	N/A	25(Renewal project)
Ballast cleaning/replacement	With renewal	N/A	With renewal	N/A	25(Renewal project)
Ballast resurfacing	10	N/A	10	N/A	4(Krezo et al., 2016)
Rail head grinding	10	N/A	10	N/A	1(Du and Karoumi, 2013)

Table 4.8-Energy consumption in Demolition stage

Activity or equipment	Turnout with FFU sleepers		Turnout with Concrete sleepers	
	Fuel	Electricity	Fuel	Electricity
	consumption (liters)	consumption (MJ)	consumption (liters)	consumption (MJ)
Ballast demolition	163	N/A	260	N/A
Sub-ballast demolition	285	N/A	400	N/A
Sleeper demolition	65	N/A	200	N/A
Turnout demolition	150	180	150	180

A summary of the initial and recurring embodied CO₂-e in case of using FFU sleepers and concrete sleepers is presented in Table 4.9 and Table 4.10, respectively. Note that FFU material has just been used in service for 25 years. Also, Ferdous et al. (2015) reported that FFU material has more than 50 years design life. Thus, it has been assumed that FFU has a 75-year lifetime (Kaewunruen et al., 2017). However, for using concrete sleepers, a 20- and 30-year life expectancy for railway components such as rails and fasteners has been considered (Kiani et al., 2008). Thus, the track renewal interval can be assumed to be 25 years. Even though the design service life of concrete sleepers is target at around 50 years, it is reported that they only tend to have an average 25 years lifespan in railway turnout (Kaewunruen et al., 2018; Remennikov and Kaewunruen, 2012). Ballast cleaning and replacement have been assumed to be the activities occurred within the renewal project, and two renewals have been conducted. Consequently, a 75-year lifespan in a railway turnout system is considered.

Table 4.9-FFU sleeper effect on both embodied CO₂-e and energy of a turnout

Components (material)	Quantities (kg)	Initial	Initial	Service life	Recurring CO ₂ -e(kg)*			Recurring Energy (MJ)*		
		CO ₂ -e(kg)	Energy		25-year	50-year	75-year	25-year	50-year	75-year
Rail (steel)	8181.66	22745	163633	25	22745	45490	68235	163633	327266	490899
Sleeper (FFU)	5522.63	23526	560547	75	23526	23526	23526	560547	560547	560547
Rail pad (rubber)	194.31	554	17682	25	554	1108	1662	17682	35364	53046
Fastening (steel)	1285.2	3573	25704	25	3573	7146	10719	25704	51408	77112
Rail joints (steel)	178.52	496	3570	25	496	992	1488	3570	7140	10710
Ballast (aggregates)	40669.34	211	3376	25	211	422	633	3376	6752	10128
Sub-ballast (aggregates)	88100.61	449	7136	25	449	898	1347	7136	14272	21408
Total					51554	79582	107610	781648	1002749	1223850

* Recurring embodied emissions and energy show the total embodied emission and energy in replacement components over a 75-year period.

Table 4.10-Concrete sleeper effect on embodied CO₂-e and energy of a turnout

Components (material)	Quantities (kg)	Initial	Initial	Service life	Recurring CO ₂ -e(kg)*			Recurring Energy (MJ)*		
		CO ₂ -e(kg)	Energy		25-year	50-year	75-year	25-year	50-year	75-year
Rail (steel)	8181.66	22745	163633	25	22745	45490	68235	163633	327266	490899
Sleeper (concrete)	20367	23526	47455	75	5642	11284	16926	47455	94910	142365
Rail pad (rubber)	194.31	554	17682	25	554	1108	1662	17682	35364	53046
Fastening (steel)	1285.2	3573	25704	25	3573	7146	10719	25704	51408	77112
Rail joints (steel)	178.52	496	3570	25	496	992	1488	3570	7140	10710
Ballast (aggregates)	101153	526	8394	25	526	1052	1578	3376	6752	10128
Sub-ballast (aggregates)	64901	331	5253	25	331	662	993	7136	14272	21408
Total					33867	67734	101601	268556	537112	805668

* Recurring embodied emissions and energy show the total embodied emission and energy in replacement components over a 75-year period.

4.3.2 Analysis of total CO₂-e performance and energy consumption

Fig.10 illustrates the total CO₂-e emission performance, which compares the uses of FFU sleepers and concrete sleepers. The railway turnout system has a lifespan of 75 years. The results present the total CO₂-e emission at the time of 25 years, 50 years and 75 years (end of lifespan). It can be seen that at 25 years, the total emission for using FFU sleepers is around 1.5 times the emission of concrete bearers. However, the total amount has exceeded in the case of using concrete sleeper at the end of lifespan. This is because two renewals have been conducted for concrete sleepers and greater amount of materials (and energy) would be required.

Fig. 10 Total CO₂-e emission performance after 25, 50 and 75 years.

Fig. 11 Total energy consumption after 25, 50 and 75 years.

Fig.11 visualises the sensitivity of service lives on the performance of total energy consumption, which is compared using FFU sleepers and concrete sleeper over a 75-year's lifespan. Consequently, the same figure indicates that the energy consumption for FFU sleepers is more than 2 times that of using concrete after 25 years construction.

The main reason behind this scenario is that the embodied energy of FFU is much higher than that of concrete in general. Moreover, a greater amount of construction machines would be demanded for both concrete sleepers laying and ballast spreading. De Greef (2006) confirmed that concrete sleepers cannot be recycled for any construction purpose but only for using as aggregate by crushing.

4.4 Discussion

Although there are some composites that cannot be recycled like plastics, it is known that FFU material is generally environment-friendly after construction. This means that no more pollution is produced during its operation lifespan. The environmental effects and failure reasons associated with each type of bearers are summarized in Table 4.11. As can be seen, the considerable loads (Kaewunruen and Remennikov, 2008) and sulphate attack (Neville, 2011) result in failure of concrete sleepers. Moreover, Table 4.12 provides a summary of general properties, presenting a comparison with different type of sleepers in relation to practicability.

Table 4.11-Environmental effects and failure reasons of different sleepers

MATERIALS	Environmental effects	Failure issues
Timber	<ul style="list-style-type: none"> ·Need a significant number of tree cutting ·Using a large number of toxic chemicals for anti-corrosion treatment during manufacturing that may affect environment. - Short life span when exposed to hostile environments (<10 years) 	<ul style="list-style-type: none"> ·Insect attack ·Not resistant to water and fire ·High load lead to breakage and settlement. - High movement of fasteners causing derailment risk.
Concrete	<ul style="list-style-type: none"> ·A lot of carbon dioxide emitted during manufacturing (Ferdous et al., 2015). ·Consumption of large amount of resources during transportation due to its heavy weight. ·Lower recyclability rate due to sulphate acid alkali attack (Silva et al.,2017). 	<ul style="list-style-type: none"> ·Corrosion ·Crack ·Sulphate attack
FFU	<ul style="list-style-type: none"> ·Also produce a lot of carbon dioxide due to high temperature manufacturing. 	<ul style="list-style-type: none"> ·High damping characteristic in low frequency region (Kaewunruen, 2014b).

Table 4.12-General properties of different sleepers (Silva et al., 2017; Manalo et al., 2010)

Materials	Timber	Concrete	FFU
Adaptability	Easy	Difficult	Easy
Workability	Easy	Difficult	Difficult
Durability	Low	High	High
Maintenance	High	Low	Low
Availability	Low	High	Low

As mentioned earlier, concrete bearers used in turnout can last around half of their estimated lifespans (Kaewunruen et al., 2018; Remennikov and Kaewunruen, 2012). Composite materials like FFU are almost maintenance-free, and therefore, has an enhanced life-cycle, making it a suitable alternative for specific areas such as tunnels, bridges, and turnouts (Griffin et al., 2015). Added to this is the widespread use of composite materials, which makes them more adaptable to environmental concern to achieve strategic choices for sustainable development.

It has also been proved that using fibre composite sleeper emits lower amounts of CO₂-e and consumes less energy compared to timber bearers (Manalo et al., 2010). Thus, it is a good alternative material for exiting timer sleepers (which tend to have a much shorter lifespan). Another advantage is that FFU sleepers are produced continuously, it is possible to get any length according to the turnout requirement (Takaia, 2006). Nevertheless, based on the Japanese code JIS Z2101 (Takaia, 2006), synthetic sleepers like FFU material shows a better performance in the long term view. However, the performance of composite materials needs further study due to the lack of practical research on design standards (Kaewunruen, 2014b; Ferous et al., 2015). Indeed, the manufacturing of recycled composite sleepers shows a remarkable reduction in GHGs (Lampo, 2002). The results demonstrate that practitioners and engineers need to consider a longer design service life in order to enable a more carbon-efficient infrastructure systems. Multiple options for recycling and maintenance regimes should be further developed to aid the sustainable development (Duan et al., 2018).

5 Conclusion

This study highlights the comparison between the uses of concrete sleepers and FFU sleepers/bearers for life cycle performance. The evaluation has been based on the calculations of CO₂-e emissions and energy consumption. Moreover, the recyclability of using FFU sleepers/bearers in a turnout system has been discussed.

Results show that using FFU sleepers/bearers initially emits more CO₂-e emissions compared to concrete bearers. Nevertheless, the use of composite materials like FFU are a better choice to achieve a more sustainable goal in the longer-term perspective. Note that the energy consumption when using FFU material is particularly higher than that of concrete. However, the high maintenance frequency and low lifespan of concrete sleepers/bearers (and timber counterparts) have been found in a railway turnout. As a consequence, FFU material performs better in special areas that are not convenient for maintenance. Notwithstanding, there are several obstacles to widespread application of

recycled composite materials. On the other hand, there are no specific design criteria for composite sleepers, which may cause safety risk over their service life. So far, FFU sleepers/bearers have only been in services for 40 years. It is necessary to undertake further research to meet the requirements and granted approval for the safe use in railway sleepers. Besides, prohibitive cost will also restrain their widespread application.

Additionally, the evaluation of end-of-life assessment on waste recycling and recovering process, which illustrates how material properties can directly influence R_{cyc} and R_{cov} . Result shows that the quota of approximately 93.50% of materials can be taken into account as a recoverable resource. What is more, a sensitivity analysis reveals the reasonable fluctuation of R_{cyc} and R_{cov} . Thus, it is believed that the technological advancement in the future will optimise recycling and recovering process, which could lead to an even more sustainable development.

To date, railway transport has become one of the most efficient forms of transportation. However, a large amount of waste have been produced due to the significant use of materials with high environmental impacts, which are often left in landfill sites. The evaluation presented in this paper will provide a better decision for material selection for a turnout system. It is clear that the use of composite materials will reduce the maintenance frequency of the railway industry. Nevertheless, establishing a comprehensive design standard can ensure the safe operation of future railway systems. It is believed that low-carbon and high-recovery composite materials can lead to sustainability.

It is important to note that this research has also taken into account the maintenance phase. However, limited maintenance activities (which are known) have been considered in this study. As a matter of fact, a huge amount of activities could result in carbon emission during the reconstruction phase. Moreover, the energy consumption of machinery used is difficult to estimate. As a consequence, the data source used in this research may be different from project to project, which can be dependent on scope and detailed process. Notwithstanding, this research can still be used as a reference for future turnout system study. Therefore, with these limitations, a more comprehensive assessment is required for future work which would be focused on cost analysis and wastes treatment. Additionally, due to insufficient data are available for analyzing 4Rs of railway turnout components, further research is needed to provide adequate data support. Future research will embark on more investigations into the recycling process of composite materials and the adaptive maintenance regimes that could enable more carbon-efficient solutions for the applications of composite materials in railway infrastructure systems.

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[illegible]

GENERAL ARRANGEMENT - TANGENTIAL TURNOUT 250:10.5

RIGHT HAND TURNOUT - AS DRAWN

LEFT HAND TURNOUT - MIRROR IMAGE