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Digital Twin aided Sustainability-based Lifecycle Management for Railway Turnout Systems

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ABSTRACT

Railway turnouts or so-called 'switches and crossings' are complex systems by nature of design and construction. Railway turnouts are used to change direction of trains from one to another. They require high-quality construction and maintenance, in order to minimise rapid degradation and component failures that could result in train derailments. Due to the complexity of railway turnouts, the efficiency and effectiveness of maintenance can be improved by integrating existing practice by Building Information Modelling (BIM). This research establishes and analyses the world-first 6D BIM for life cycle management of a railway turnout system. The BIM (Level 3) has integrated 6-dimensions of field data information based on Revit-2018 and Navisworks-2018 platforms. The digital twins of a railway turnout in 3D embrace time schedule, costs and sustainability across the whole life cycle. The use of BIM for railway turnout systems has the potential to improve the overall information flow of the turnout planning and design, manufacturing pre-assembly and logistic, construction and installation, operation and management and demolition, thereby achieving better project performance and quality. Based on integrated information of railway turnout system, the 6D BIM has the ability to assess on economic, management and sustainability, and achieve a balance among them. This is the word first to demonstrate that BIM can fully deliver its essential benefits by information sharing, easing technical communication, improving design quality, reducing of design errors, accelerating implementation, speeding up work, shortening construction duration, reducing construction costs, enhancing carbon efficiency, supporting project management, and providing its owners with higher operational efficiency over the railway turnout system life-cycle. The results reveal that embodied material emission is the main contributor towards carbon footprint, especially produced during the manufacturing stage. The reconstruction stage contributes the most expensive phase of life cycle. The insight will significantly benefit the co-value creation among engineers, project managers, technicians, and senior management team.

Key words: BIM; 6D; digital twin; turnout; Level 3 model; IS; schedule; costs; carbon; life-cycle

1 INTRODUCTION

Railway turnout (or so-called 'switch and crossing') is a special track system used to divert a train from a particular direction or a particular track onto other directions or other tracks. It is one of the most complex and nonlinear systems in railway infrastructure network. As a critical infrastructure, it is a structural grillage system that consists of steel rails, points (or called 'switches'), crossings (or called 'frog'), steel plates, rubber pads, insulators, fasteners, screw spikes, beam bearers (either timber, polymer, composite, steel or concrete), ballast and formation (Kaewunruen, 2014). Traditional turnout structures are generally constructed using timber bearers. The timber bearers allow the steelwork to be mounted directly on steel plates that are spiked or screwed into the bearers. In present day, concrete bearers are the most popular choice, and fibre-based composite bearers (i.e. FFU) have recently been adopted (Kaewunruen et al., 2017). Modern turnouts have adopted tangential geometry to smooth the ride quality and have installed concrete bearers to stabilize the track structure. The turnout structure generally imparts high impact forces on to its structural members because of its acute geometry and mechanical connections between closure rails and switch rails (i.e. heel-block joints). Since the railway turnout is complex, a small deviation from the original design can easily incur from human errors, poor workmanships, machinery errors, accidents, measurement inaccuracy, and so on. This small deviation however can cause significant problems to railway systems, such as causing high-intensity impact loading, excessive lateral force, hunting behaviour, poor ride comfort (from jerking behaviour), and potentially train derailments over a complex geometry (Dindar et al., 2017; 2018). Accordingly, the reconstruction and maintenance activities for railway turnouts should be very careful to minimise any potential error. Due to the complexity of railway turnouts, the thorough and careful reconstruction and maintenance activities require significant time and resources. Importantly, there are many technical aspects required multidisciplinary capabilities (staff, technician, engineers, managers, etc.). A key success of the project requires seamless collaboration by various sources of personal resources, making it very necessary to establish a digital built environment that can enable and enhance efficiency and effectiveness of reconstruction and maintenance practices for complex turnout systems.

It is well known that a railway project has a big impact on the development and spatial management. The turnout system is an essential and complex section of a railway used to divert a train from one direction to other directions. Besides, it requires considerable design, manufacturing, construction, installation and operation with a specific budget during the whole life-cycle. Additionally, Sodagar and Fieldson (2008) stated that the industry of construction is turning towards sustainability, which is a major contributor to aggravate climate change. Consequently, it needs an integrate information system to well manage the railway turnout system of which its components are sophisticatedly designed, assembled, and interacted. The improvement for sustainability of design, manufacturing, construction, installation and operation will need to be co-created among stakeholders, who specialise in different and various aspects of those activities throughout the entire service life.

The technology of Building Information Modelling (BIM) or sometimes referred to as digital twin is in great demand of the world nowadays. Many countries introduce regulations to their new infrastructure projects for the application of BIM. BIM is being considered an Information System (IS) where tacit knowledge and can be stored and retrieved from a digital database making it easy to take prompt decisions as information is ready to be analysed. BIM at the model element level entails working with 3D elements and embedded data, therefore adding a layer of complexity to the management of information along the different stages of the project (Barrera et al., 2018). It is demonstrated that BIM or digital twin can then be used to help thoroughly visualize and prioritise maintenance options, promote collaboration among stakeholders, and accurately estimate associated costs and associated technical issues encountered by physical constraints at any pre-determined location (Kaewunruen et al., 2018; 2019).

The UK Government (2013) published its comprehensive 2025 targets for Construction: lower costs, faster delivery, lower emissions and improvement in export. Only the implementation of BIM will be able to deliver more sustainable building, more quickly and more efficiently. Chevin (2012) identified that BIM has been mandated as part of the government's drive for to shave 20% from construction costs. Consequently, it is quite important and very useful to bridge the gap between railway turnout system and BIM. This research focuses on the development of BIM for railway turnout systems and the life cycle analysis to improve effectiveness, efficacy and sustainability of the design, manufacturing, construction, installation and operation activities throughout the entire service life. This study will get clearer details of every element and component in the railway turnout system, and will get various integrated information across the railway turnout system lifespan. Therefore, the railway turnout system can be thoroughly visualised, better performed and better managed in each stage of the whole life-cycle. This study is thus the world first to establish a 6D BIM for railway switches and crossings, taking into account lifecycle consideration. The BIM will be very beneficial to engineers, technicians, project managers, senior management, and other stakeholders by sharing better information, by communicating better technical complexities, and by quantifying cost, risk and sustainability for maintenance decision making.

2 LITERATURE REVIEW

2.1 Building information modelling (BIM)

2.1.1 Defining BIM

BIM or Building Information Modelling is a process for creating and managing a model containing digital information about a specific asset across its whole life-cycle (Simpson, 2015). According to PAS 1192-2 (2013), BIM is a coordinated digital dataset that contains appropriate computable information necessary to design, build, operate and ultimately decommission a project in the construction area.

NBS (2016) reported that creating a digital Building Information Model enables those who interact with the asset management to optimize their actions, resulting in a greater whole life value for the asset. One of the key outputs is the Building Information Model, the digital description of every aspect of the built asset. This model draws on information assembled collaboratively and updated at key stages of a project. In a nutshell, sharing structured, consisted and continuous information is the very essence of BIM.

2.1.2 BIM life-cycle

Doumbouya et al (2016) stated that the life-cycle building stages encompass inception, brief, design, production, maintenance and deconstruction. Figure1 shows that BIM is at the heart of the asset life-cycle. It can be seen that many stakeholders are distributed over the BIM life-cycle. The work of BIM is to pull the information from stakeholders together, and shares it to improve the asset outcome for the customer and others.

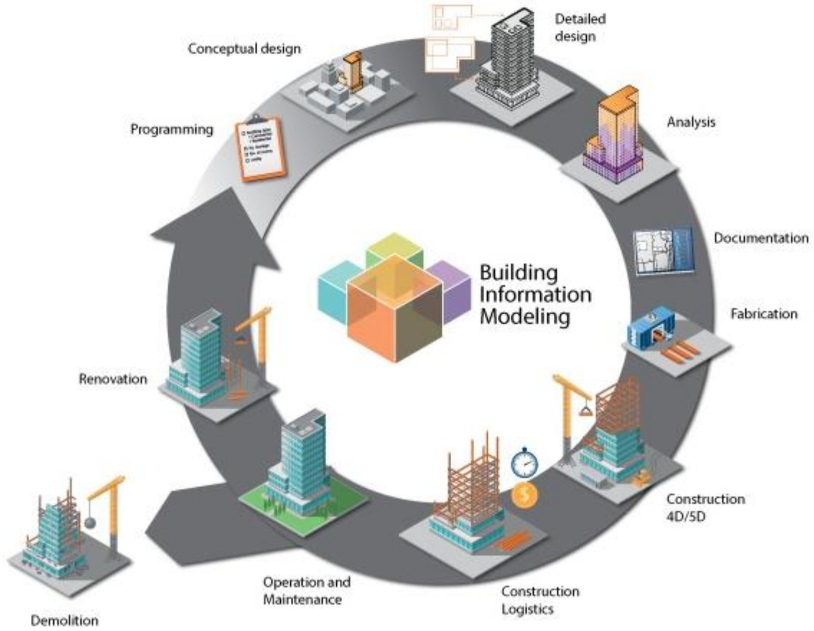


Figure 1: Building information modelling life-cycle (Gajera, 2017)

2.1.3 Levels of BIM maturity

According to BIM Talk (2016), BIM is being used at different levels of sophistication. Figure 2 shows a metric of the ability of the construction supply chain to operate and exchange information as applied by the UK Government BIS BIM strategy Report.

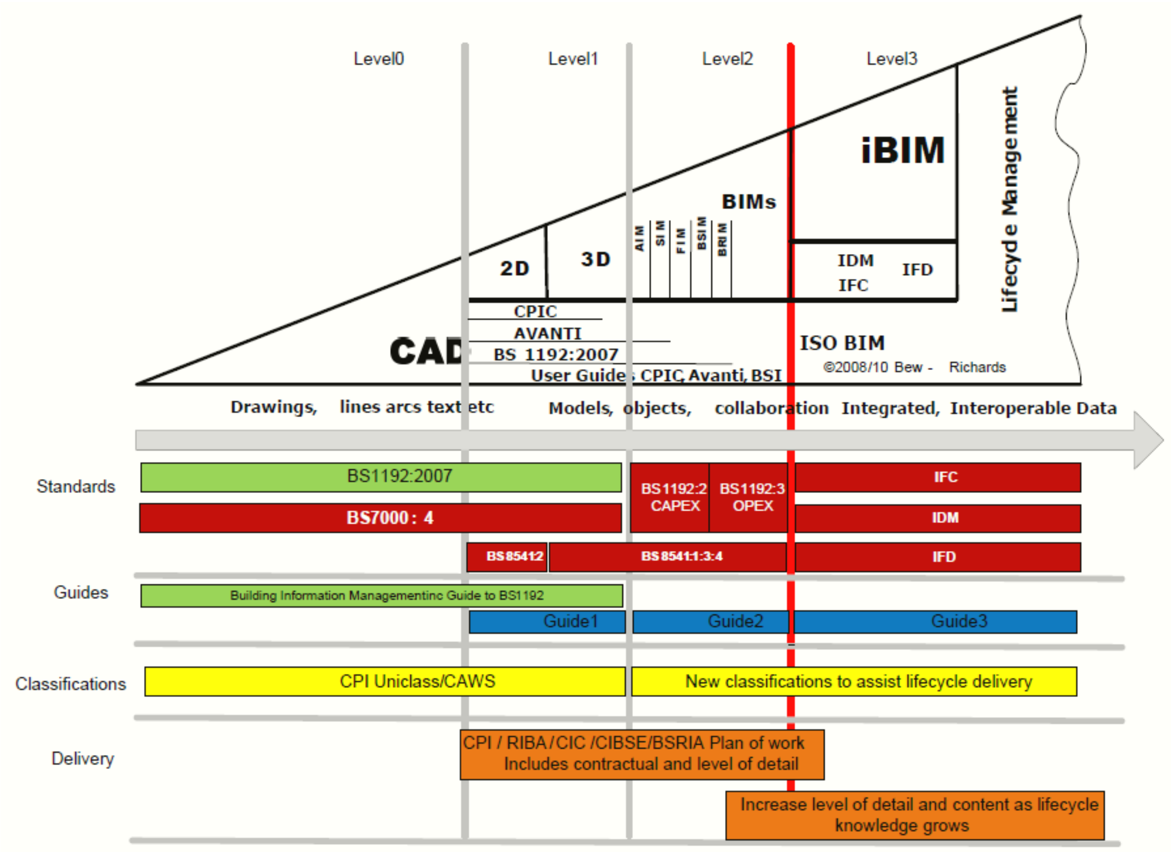


Figure 2: BIM maturity metric (BIMTalk, 2016)

Table 1: Levels of BIM maturity (BIMTalk, 2016)

Classification	Description
Level 0	Unmanaged CAD, in 2D, with paper (or electronic paper) data exchange.
Level 1	Managed CAD in 2D or 3D format with a collaborative tool providing a common data environment with a standardised approach to data structure and format. Commercial data separate.
Level 2	A managed 3D environment held in separate discipline 'BIM' tools with data attached; Commercial data will be managed by enterprise resource planning software and integrated by proprietary interfaces or bespoke middleware. 4D construction sequencing, 5D cost information.
Level 3	A fully integrated and collaborative process enable by 'web services' and compliant with emerging industry foundation class standards. 4D construction sequencing, 5D cost information and 6D project life-cycle management information.

Table 1 illustrates the relationship between Levels of BIM maturity and different dimensions of BIM. Levels of BIM maturity categorize the types of technology and collaboration work to sufficiently describe and understand the processes, techniques and tools to be used. The world is believed to be operating at maturity level 2 where managed 3D environment is held in separate BIM disciplines and with the possibility of holding and managing 4D programme data as well as 5D cost elements (Henry, 2014). The possibility of expanding the BIM scope (6D to nD modelling) has already been demonstrated by researchers in various extensions. According to the attribute of railway turnout system, we develop the 6D dimension of BIM as the GHG analysis information across the life-cycle of this project.

2.2 Railway turnout system

2.2.1 Railway turnout system assembly

Railway turnouts are usually determined by rail operations and requirements to transfer a train from a particular rail track onto another track (Kaewunruen et al, 2015). They are complex assemblies of sections and components within a railway corridor as they constitute an exceptional discontinuity within the railway layout (Dindar et al, 2017). Kaewunruen et al (2015) stated that railway turnout is a structural grillage system that consists of steel rail, crossings, closures, points, rubber pads, steel plates, screw spikes, fastening systems, sleepers, ballast and foundation. Generally, railway turnout system consists of complicated connections, which are designed with special geometries (sizes and dimensions), curvatures (angles and grades) elements and with different profiles, as shown in Figure 3. All of the properties of the railway turnouts make them difficult to be designed, manufactured, constructed and managed across the whole life-cycle.

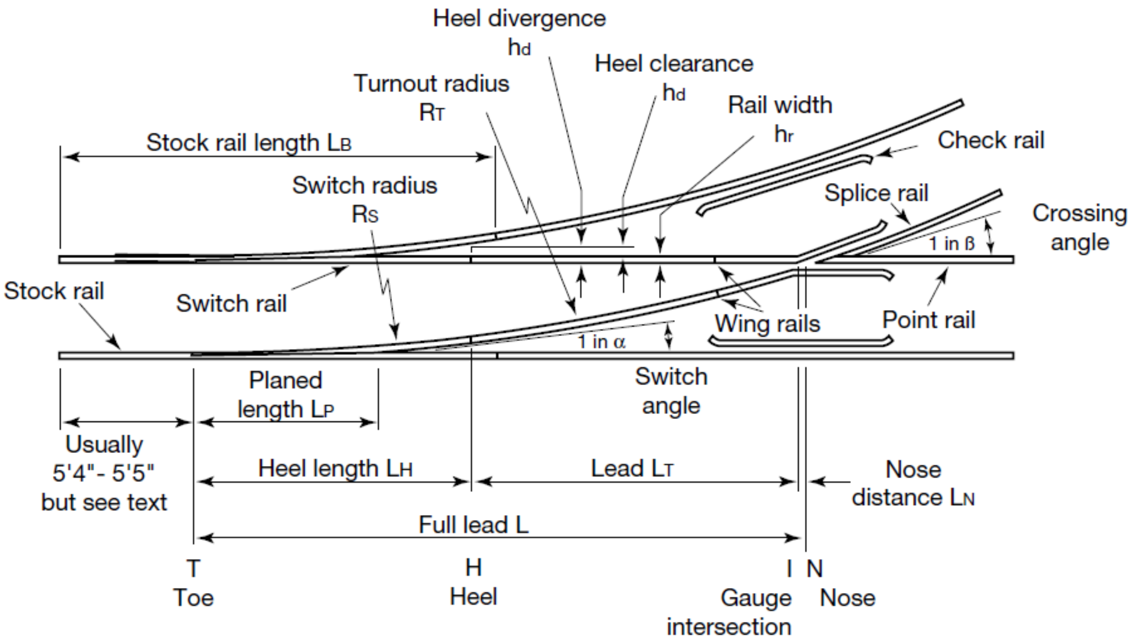


Figure 3: The geometry of a turnout (Gauge O Guild, 2004)

Besides, railway turnout is the component of railway infrastructure to have the highest risk to fail. For example, each of design, manufacturing, installation and operation control inaccuracy can result in failure on track and potentially result in a derailment situation. In other words, it is crucial that railway turnout project should try to ensure a sufficient and accurate information system in its life-cycle.

2.2.2 Stages of a railway turnout system project

2.2.2.1 Planning and design stage

Railway turnout life-cycle begins with planning and designing stage, which is on the basis of actual demand. To ensure that the best fit for every project is designed, it must be met with the requirements of the eventual end user. Besides, it is essential for understanding correctly what the client expects from the installation and the extent and type of traffic through railway turnout system. Furthermore, designers must carry out masses of investigation in the field and obtain raw data from the field, for instance, the weather condition, geology, classification of the railway, using type, the traffic data, etc.

Collaboration in Design is the essence. An example for rail profiles is designed according to their operational requirements such as the section shape, loading, geometry, etc. Level of Development (LOD) is used for coordinating modelling efforts between multiple parties (Barrera, 2017). The early design has to be meticulous, with increased effort in the early phase, due to the fact that decisions made during this time will significantly influence the project as a whole. It is clear that integrated design plays an essential role in the whole life-cycle of a railway turnout system.

2.2.2.2 Manufacturing stage

According to the designing model, manufacturing plants start to produce each part of the railway turnout system including steel rail (block rail, point rail, closuring rail and frog rail), rail pads, concrete sleepers, fastening systems and switch controlling system, etc. In this stage, it is significant to ensure that the information delivered from designers to manufacturer is precise. A good way is to establish an ID of each component with sufficient materials and manufacturing information in the model, and keep the consistency in delivery.

2.2.2.3 Pre-assembly (pre-build) stage

Usually, when the manufacturing stage is over, it begins to pre-assemble in the factory. Pre-assembly is a crucial stage for issues to be identified and rectified prior to installation. At this stage, it is quite important to attach the information of assemblies to the model, for example, where a specific component is placed in the 3D model and what is the date of that component pre-assembled. These kinds of information will be the key evidence that determines management and maintenance in the future.

2.2.2.4 Logistic stage

The logistic of the turnout project is the transportation from pre-assembly site to installation site. Railway turnouts are large pieces of rail infrastructure which may be super-long extra-wide, or overweight. It is crucial to choose an appropriate way to transfer the pre-assembled turnout to installation site such as by railway or highway. Other information of logistics includes distance, obstacles, stations and means of transportation, etc.

2.2.2.5 Reconstruction and installation stage

Foundation construction and turnout installation are carried out in a grey field environment. Before sub-ballast construction, surface cleaning and some preparation work are needed. Paixao and Martins (2015) stated that sub-ballast layer plays a fundamental role in the track behaviour. Only when the standards of the sub-ballast have met the requirements, the follow-up work can proceed smoothly. The methodology of the ballast is roughly the same with sub-ballast. After foundation construction, it starts with installation of rail turnout. At this stage,

2.2.2.6 Operation and Maintenance stage

Railway traffic includes passenger trains and freight trains which is divided into different train services. The operation of railway turnout is a kind of infrastructure management. This includes the daily use for railway traffic and maintenance management. Besides, the switch motor that is operated by a remotely controlled electric motor to move the points from one position to the other.

Esveld (2001) illustrated that the process of maintenance involves the effective use of materials and maintenance techniques to enable assets to extend their operational life. Railway turnout system maintenance can be divided into six main categories including:

- Rail geometry
- Track geometry
- Track structures
- Level crossing
- Ballast bed
- Miscellaneous

Esveld (2001) also suggested that systematic maintenance is often referred to as mechanised maintenance and can be carried out using the following activities.

- Rail-grinding machines – to remove corrugations and grind welds
- Tamping machines, to correct level, cant and alignment
- Ballasts regulators – to establish correct ballast profile
- Stabilisers – to compact ballast
- Ballast cleaner – to clean ballast bed
- Components replacement (fastening system, bolt, pads and steel rail)

2.2.2.7 Demolition stage

Demolition stage occurs when the railway turnout system lifespan is reached. In the UK, demolition construction is usually conducted during some specific time such as weekends. As a consequence, there is a need to close the railway line during the demolition construction period. Various machines and equipment are used at this stage including cutting machine, front end loaders, crane, truck, etc.

2.2.2.8 Recycle / Renewal

Railway turnout possession can be recycled after demolition. For example, the worn and unusable rail track can be installed in a lower standard railway to continue use or recycled by the steel manufactory. And the position of turnout will be replaced to a new turnout completely, which means a new life-cycle starting.

2.3 The GHG emissions calculation

The GHG emission calculation is about an organization's activity data gathering and transferring this into one or more quantity of greenhouse gas. GHG emission source in the context of turnout life-cycle is an activity that results in the emission of greenhouse gases. In a railway turnout system lifespan, there are mainly three sources that result in GHG emission. They are Electricity use, Fuel consumption and Embodied materials.

Normally, a single activity type can produce more than one type of greenhouse gas. For instance, the burning of natural gas typically produces CO_2, CH_4 and N_2O. Rawlinson and Weight (2007) stated that Carbon dioxide (CO_2) is the dominate gas of greenhouse gas emissions, because global warming potentials are based on CO_2. The results of applying a GWP are expressed in carbon dioxide equivalent (CO_2-e). Values of GWP are periodically refined as newer science becomes available.

The emission factor (EF) is a rate of coordinate to the amount of greenhouse gas emitted from the given unit of activity. Typically, when an emission factor is listed, it would be listed with a unit of quantity of greenhouse gas over a functional unit of activity. Some examples are listed below: emission factors are often provided by government institutions such as US EPA, UK GHG or environment Canada. Emission factors may also be obtained from the utility and service providers and academic and scientific research papers.

The UK Government GHG Conversion Factors for Company Reporting (2018) stated that:

Table 2: Factors for Electricity and Diesel (BEIS, 2018)

Activity	Country	Unit	Year	kg CO_2-e	kg CO_2	kg CH_4	kg N_2 O
Electricity generated	UK	kwh	2018	0.28307	0.28088	0.00066	0.00153
Diesel (100% mineral diesel)	UK	litres	2018	2.68779	2.6502	0.00042	0.03717

The embodied CO2-e factors are obtained from the ICE (2011) database and Krezo et al (2016) illustrated that embodied emissions factors of railway infrastructures as follows:

Table 3: The embodied CO_2-e factors (Krezo, 2016)

Materials	Unit	kg CO_2-e
Road base	kg	0.0051
Ballast	kg	0.005
Concrete sleepers	kg	0.277
Steel rail	kg	2.78
Plastic pads	kg	3
Insulators	kg	3
Resilient	kg	2.78

3 METHODOLOGY

The process of establishing railway turnout system information modelling is a special method to develop a database as a sharing platform. A great amount of data information is delivered from different resources, which can be used in the railway turnout system life-cycle. Generally, there are five primary steps to be followed to build up a 6D BIM of railway turnout system.

Initially, according to literature review of the progress of turnout project, it is possible to generate a specific life-cycle of railway turnout system. The whole life-cycle can be divided into several different phases, which represent different major stages with key tasks inside.

Based on 2D drawing of turnout layout and standard profiles, 3D model can be built by using the software of Revit-2018. As Revit is usually used for real building model, this special section of railway turnout system needs to be established special components in different families: Firstly, establish 3D model with accurate dimensions from 2D drawings; Then, organize these different components into a project model; Finally, set up specific parameters and add coordinate materials information to this 3D model.

4D model is on the basis of a 3D model with a time schedule of the turnout system project. As it is a new construction, there are two types of schedule to be established in this project. The 3D model should be initially exported from software Revit-2018, and then be imported to software Navisworks-2018. Following that, the project life-cycle schedule will be added to this model. Finally, each time slot should be attached to the coordinate component of the model. Therefore, the 4D model can be established on the timeline of the project. On the other hand, the major duration of this project rests in the operation and maintenance phase.. A brief asset management schedule for is to be generated from Revit-2018.

5D model comprises of a 4D model and the cost data, which mainly includes two types of sources: the material cost and the multi-category cost. The materials cost is based on the price of raw material, while the multi-category cost represents the total budget. All kinds of cost data are to be added and a total budget is to be generated by Revit-2018.

For 6D model, firstly, inclusions and exclusions is to be established, next step is navigating each stage of a turnout life-cycle and gathering activities data; after that, it is transferring these data into one or more quantity of greenhouse gas. According to the UK Government GHG conversion Factors for Company Reporting (2018) and academic papers, equations of carbon emission calculation and analysis are assisted to build up the 6D model. The standard method to evaluate carbon footprint (GHG emission) from reconstruction, maintenance, and operations activities throughout the life cycle can be noted as follows:

GHG emissions = activity data × emission conversion factor (BEIS, 2018)

$$\mathrm{EM} = \sum_{k=1}^{N} EF_K QM_K$$ (Krezo et al, 2016)

$$E_{ij} = \mathrm{Q}_i C_i F_{ij}$$ (Krezo et al, 2016)

$$E_U = \frac{\sum E_{ij}}{T}$$ (Krezo et al, 2016)

After all the GHG emissions calculation for each activity is finished, they can be summed up to provide a total value of the GHG emissions.

4 RESULTS

4.1 A defined rail turnout life-cycle

Based on the process of the turnout project, the rail turnout system life-cycle is generated in terms of BIM life-cycle model. Figure 4 shows the real life-cycle of the railway turnout system. It begins with the planning and design stage, which is an essential phase that all of the stakeholders can involve in. The second phase is manufacturing, pre-assembly and logistic, which is a stage of turnout components production, components pre-assembled in the plant and turnout transportation to the construction site. Following that is the reconstruction and installation phase including ballast and sub-ballast construction and turnout installation on site. After that, the project will be handed over to the user and become an asset management phase which contains operation and maintenance. The final stage is demolition, which indicates the end of the turnout lifespan. After the demolition, the turnout could be either be recycled or renewed. It will restart a new life-cycle.

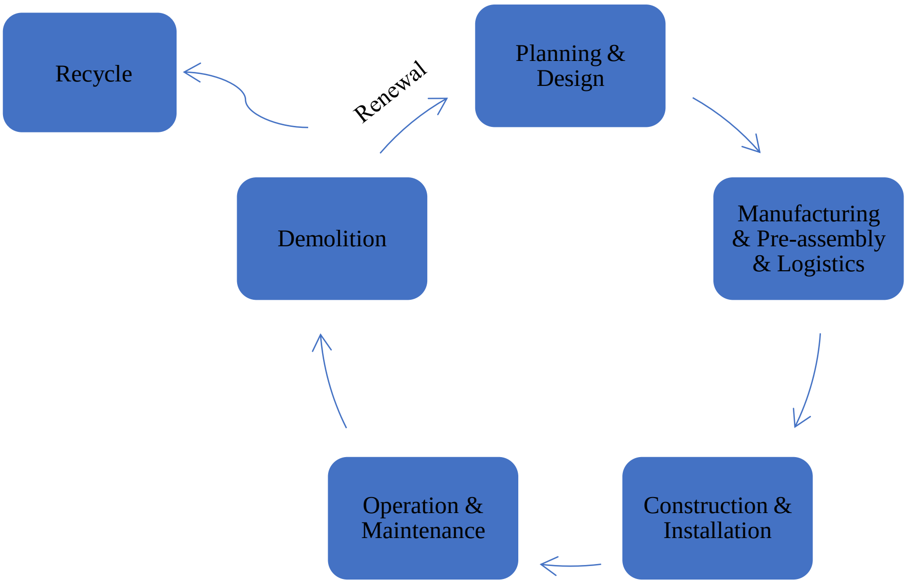


Figure 4: Railway turnout system life-cycle

4.2 Integration of different parametric 3D models

In this project, the original 2D drawings and the adopted parameters of 3D modelling are collected to conduct detail designs. Figure 5 visualizes the plan dimensions of a tangential turnout. Figure 6 shows the profile of UIC 60 (EN 13674-1) being used as the standard profile of the turnout track. 2D drawings illustrate that the railway turnout consists of complicated geometry parameters both in the layout and standard profile.

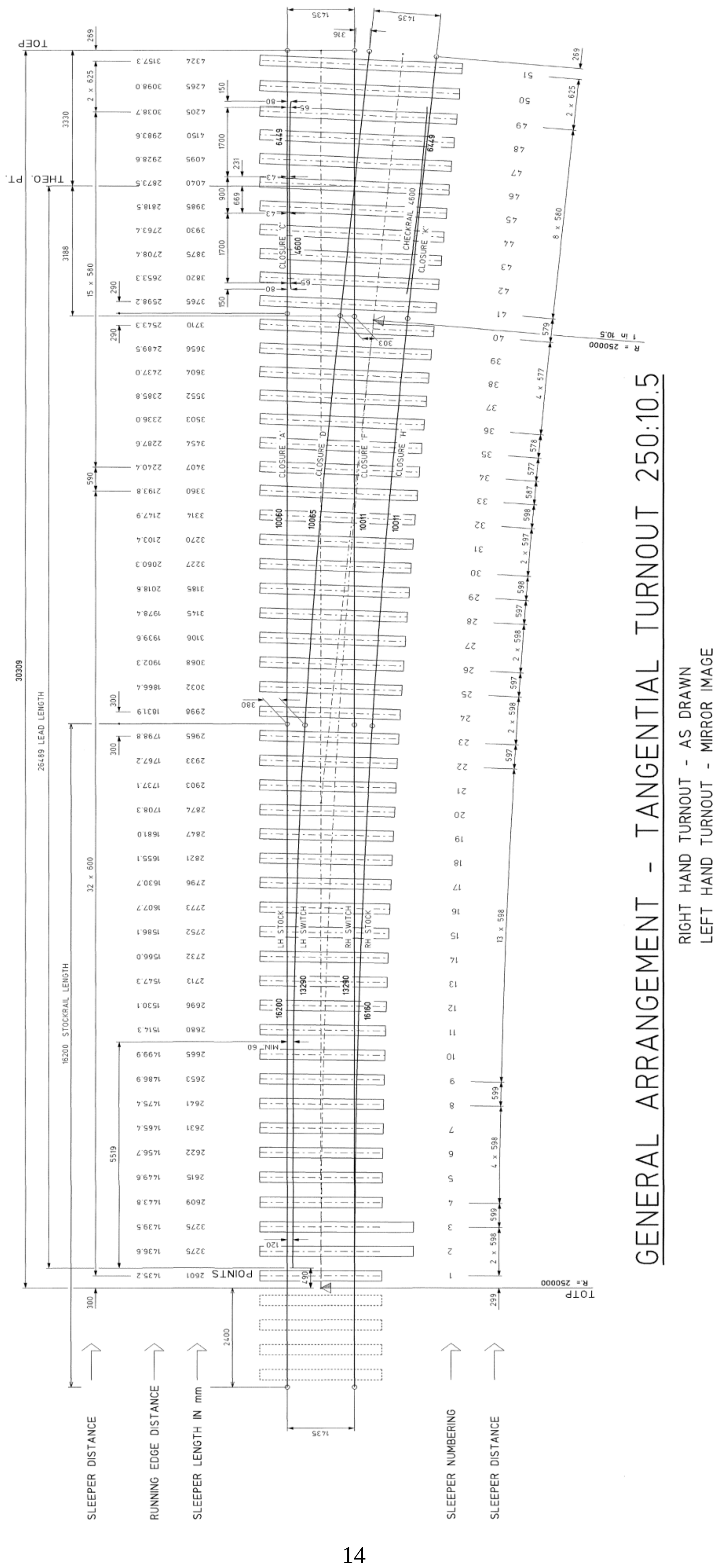


Figure 5: Figure Layout of Tangential turnout (RailCorp, 2007)

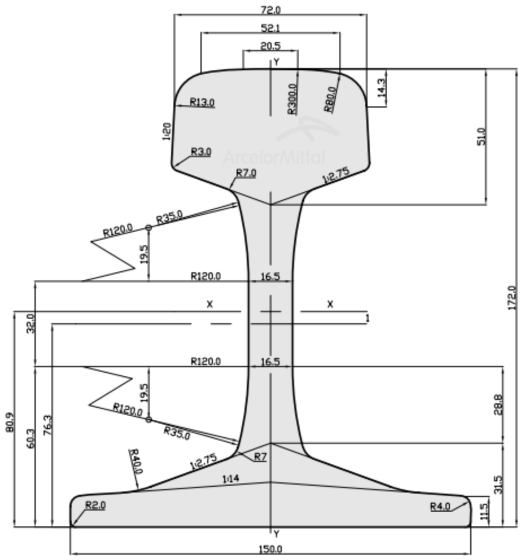


Figure 6: Profile of Standard UIC60 (EN 13674-1)

In the Revit Platform API, it is possible to complete the 3D Sketch by using the following classes: Extrusion, Revolution, Blend and Sweep (Revit Guide, 2014). Based on the 2D drawing of the layout, profile, exponents of a turnout, it is feasible to create a 3D simulation modelling accurately and visibly in Revit-2018 as shown in Figure 5.

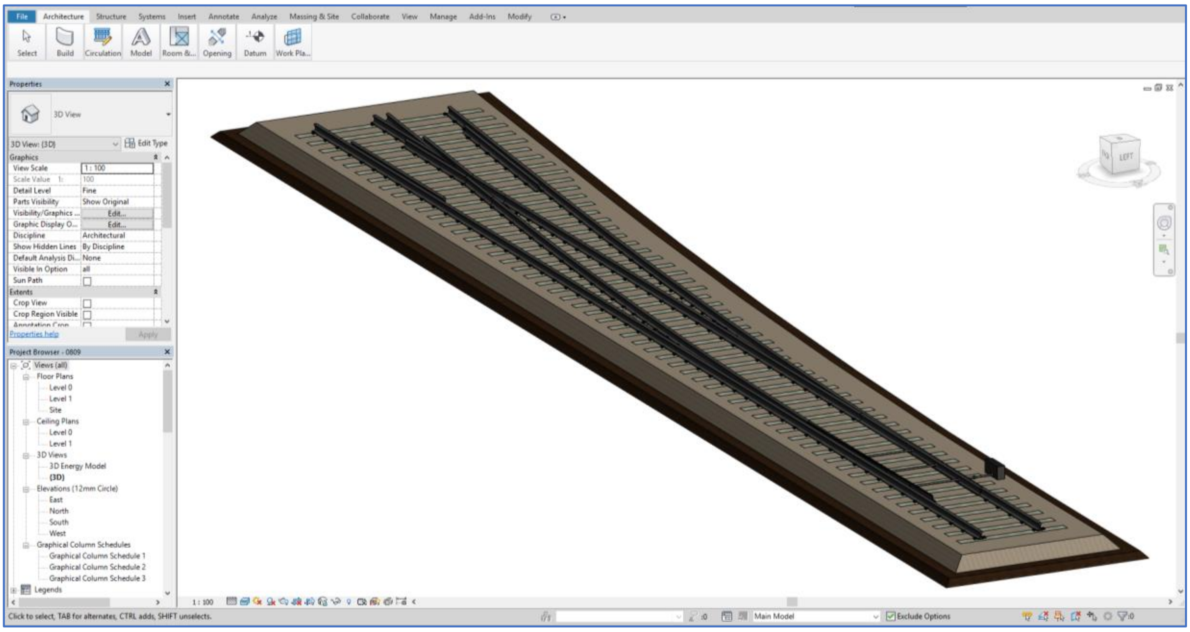


Figure 7: Complete 3D model of turnout system

As each component is a sole family in Revit-2018, the result of the 3D model can indicate the logical relations between each component. People can have an integrated view of this model from different perspectives. The 3D model enables checking and validating both geometry and information inside of the model to make sure each detailed part clear and accurate. Figure 8 demonstrates the spatial relations between steel rails, resilient rubber pads, concrete sleepers, ballast, sub-ballast, switch motor and fastening system. This BIM can be used to help visualise any hidden complex components. It can help engineers to note and plan for the location or the component with damages, requiring further maintenance activities.

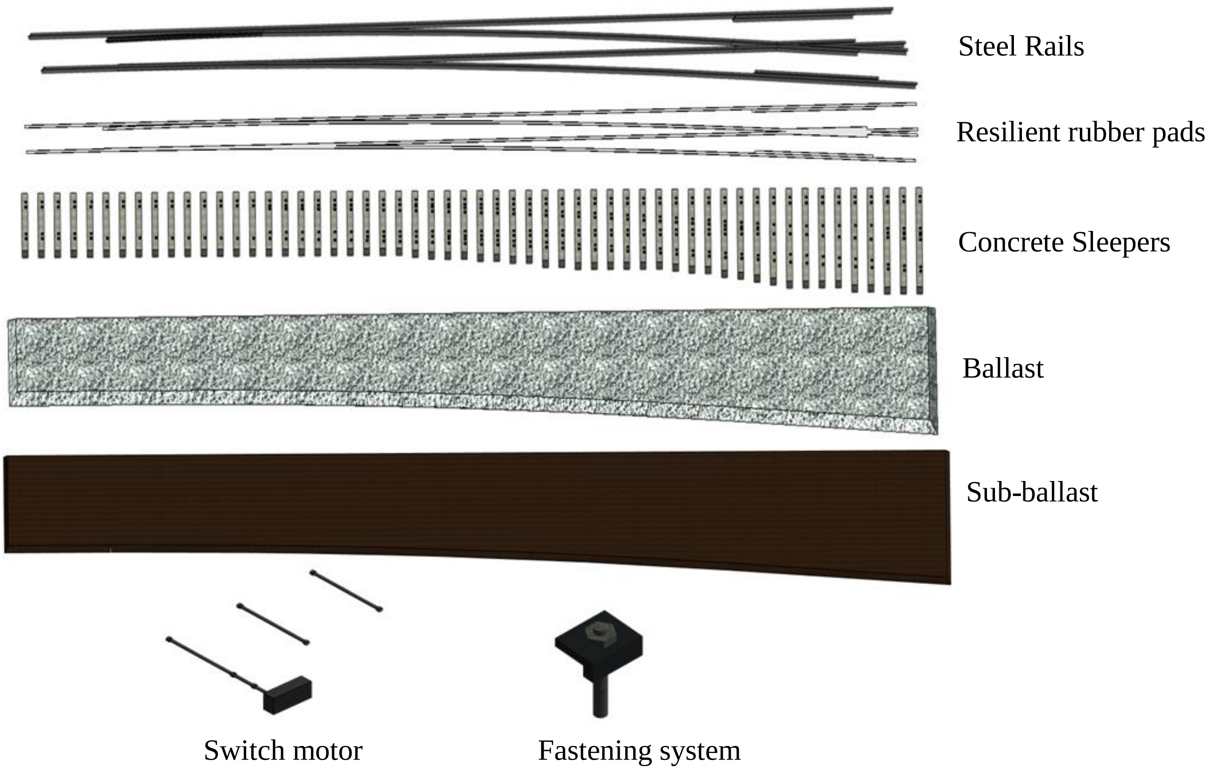


Figure 8: Integrate components in 3D turnout system model

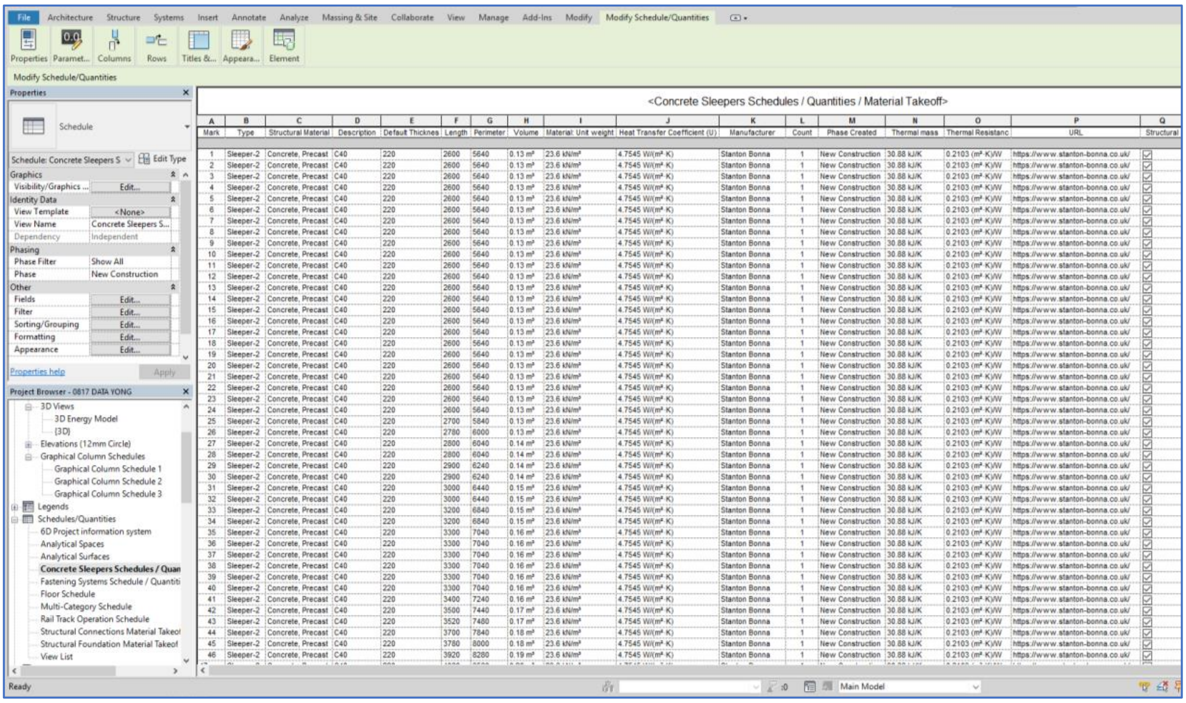


Figure 9: Concrete sleeper material take-off

Revit has a big database of all kinds of materials where the material category can be chosen and coordinate information can be applied to each component of the 3D model. Material information usually includes model, shape, quantity, dimensions, manufactures and physical parameters, etc. For instance, the sleeper material information is illustrated in Figure 7. In this project, there are seven primary materials used.

4.3 Establishing the railway turnout schedule and the 4D Model

4D turnout system model is a further development over 3D turnout system model. It adds a new dimension (time/schedule) to 3D modelling. Tian et al (2015) stated that 4D Simulation is conducted to help the client, contractors, and users to establish a reasonable project schedule in the whole life-cycle. The key step to making 4D simulation implemented is to link 3D component with schedule. It works as a central platform for all the participants to have a visualization of the progress of the turnout system over lifetime.

Navisworks-2018 is such a kind of software that links the elements in the Revit model with specific project task. There is a timeline function in Navisworks-2018, which the project schedule can be added in. In this project, the 4D simulation is formed by using Revit-2018 turnout model in combination with Navisworks-2018 over turnout whole life-cycle.

With the data linked to the graphical representation of components/systems it becomes easy to understand and query project information and it is also possible to show how reconstruction will develop, sequentially, over time showing how a structure will visually appear at each stage (Mcpartland, 2017).

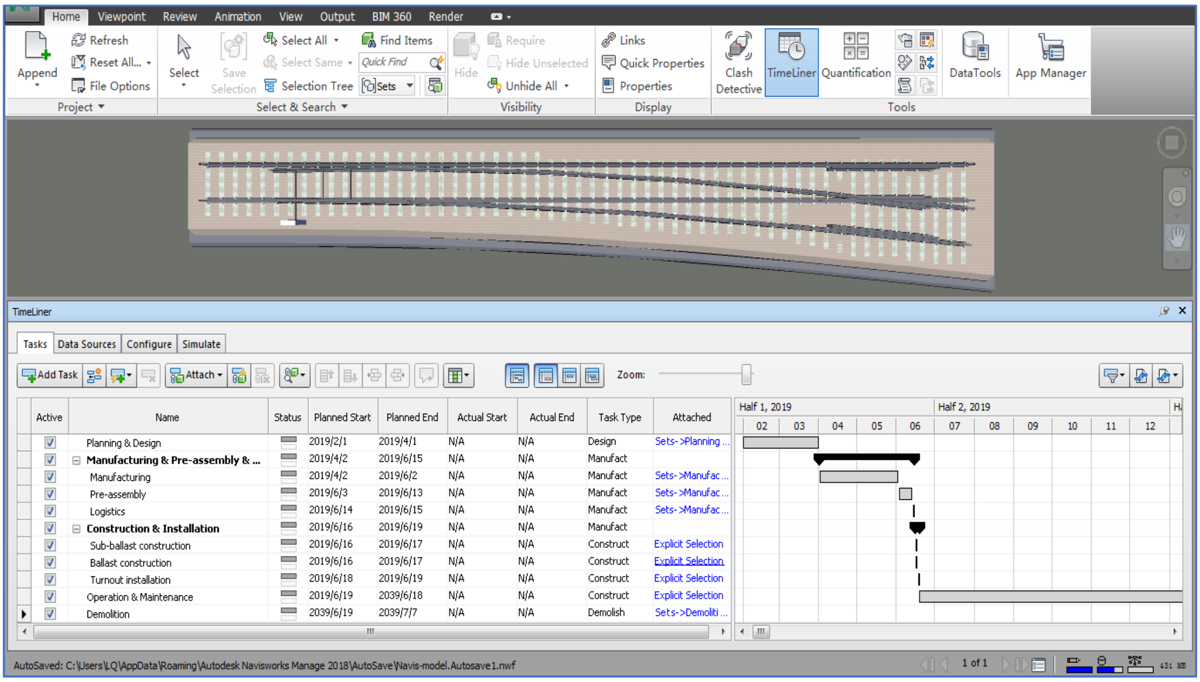
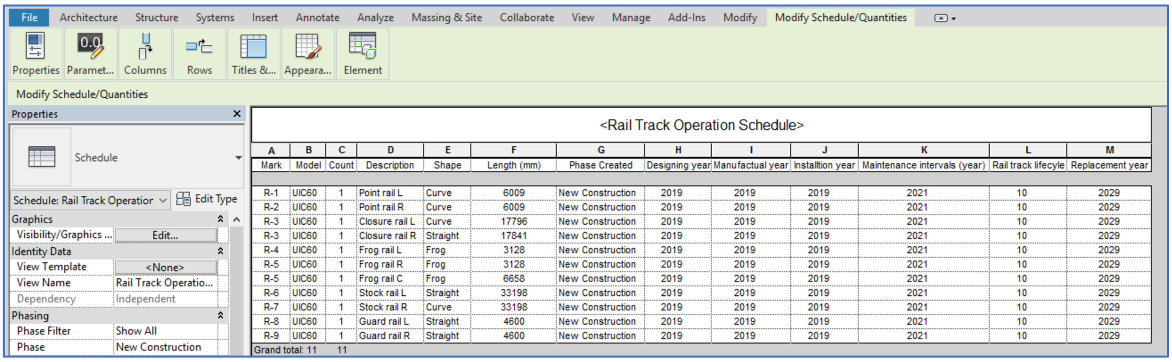


Figure 10: 4D simulation of turnout system in Navisworks-2018

From Figure8, two columns of actual start and actual end data are located behind the planned date on the timeline of the Navisworks-2018. This is essential information for comparing the time delayed in the planning and design stage. The PM (Project Manager) can easily track the schedule and real-time progress over the turnout system lifespan. Therefore, necessary actions can be taken to adjust management in the followed stages.

At the stage of manufacture and reconstruction, it is crucial to number each component for identification purpose. Some companies have already developed the mobile terminal to input assemblies ID. This information will be received by a remote device so that the status of each component can be tracked. This can be used in reconstruction management for the resource optimization.



<Rail Track Operation Schedule>

A	B	C	D	E	F	G	H	I	J	K	L	M
Mark	Model	Count	Description	Shape	Length (mm)	Phase Created	Designing year	Manufactual year	Installtion year	Maintenance intervals (year)	Rail track lifecyle	Replacement year
R-1	UIC60	1	Point rail L	Curve	6009	New Construction	2019	2019	2019	2021	10	2029
R-2	UIC60	1	Point rail R	Curve	6009	New Construction	2019	2019	2019	2021	10	2029
R-3	UIC60	1	Closure rail L	Curve	17796	New Construction	2019	2019	2019	2021	10	2029
R-3	UIC60	1	Closure rail R	Straight	17841	New Construction	2019	2019	2019	2021	10	2029
R-4	UIC60	1	Frog rail L	Frog	3128	New Construction	2019	2019	2019	2021	10	2029
R-5	UIC60	1	Frog rail R	Frog	3128	New Construction	2019	2019	2019	2021	10	2029
R-5	UIC60	1	Frog rail C	Frog	6658	New Construction	2019	2019	2019	2021	10	2029
R-6	UIC60	1	Stock rail L	Straight	33198	New Construction	2019	2019	2019	2021	10	2029
R-7	UIC60	1	Stock rail R	Curve	33198	New Construction	2019	2019	2019	2021	10	2029
R-8	UIC60	1	Guard rail L	Straight	4600	New Construction	2019	2019	2019	2021	10	2029
R-9	UIC60	1	Guard rail R	Straight	4600	New Construction	2019	2019	2019	2021	10	2029
Grand total: 11		11										

Figure 11: Rail track management schedule

For this special infrastructure, the reconstruction period is extremely short and the operation and maintenance period is apparently longer. As each component in the turnout system has its own life-cycle, it is essential to build a database for recording time information of each component in each stage. Therefore, the user can obtain integrated information about components of turnout system management. Figure 9 briefly shows the components of the steel rail should be configured and managed for optimal performance on the basis of operation schedule over the operational stage.

4.4 Developing the rail turnout cost schedule and 5D Model

Drawing on the components of the information model, and being able to extract accurate cost information is what is at the heart of 5D BIM (McPartland, 2017). Creation of 5D models enables the participants of a reconstruction project to visualize the progress of reconstruction activities and its related costs over time. An integrated 5D BIM model can update both the schedule and budget when any design change occurs. Bryde et al (2012) states that by using the integrated 5D BIM model to visualize and explore the impact of changes, the project scope in check can be kept and become a trustworthy liaison between the designers and owner.

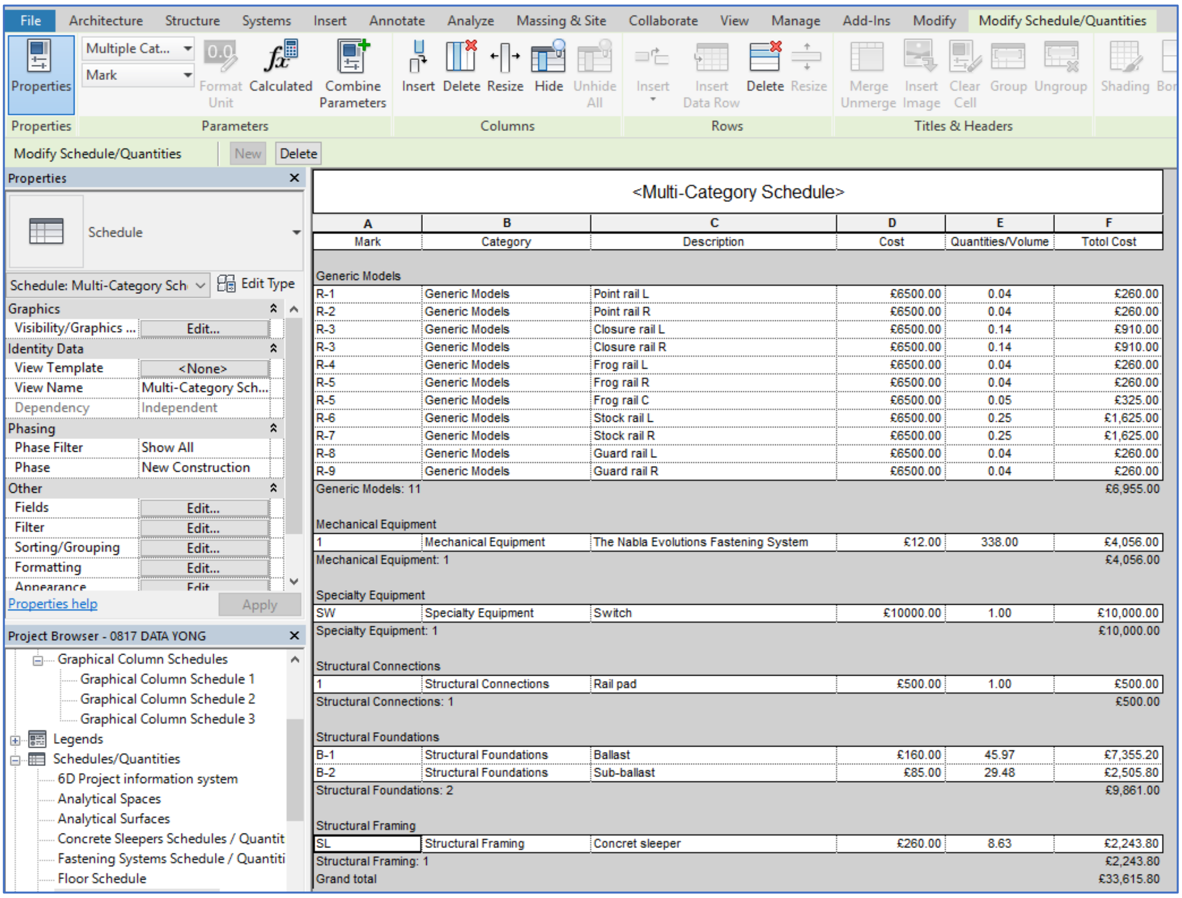


Figure 12: Multi-category Cost Schedule

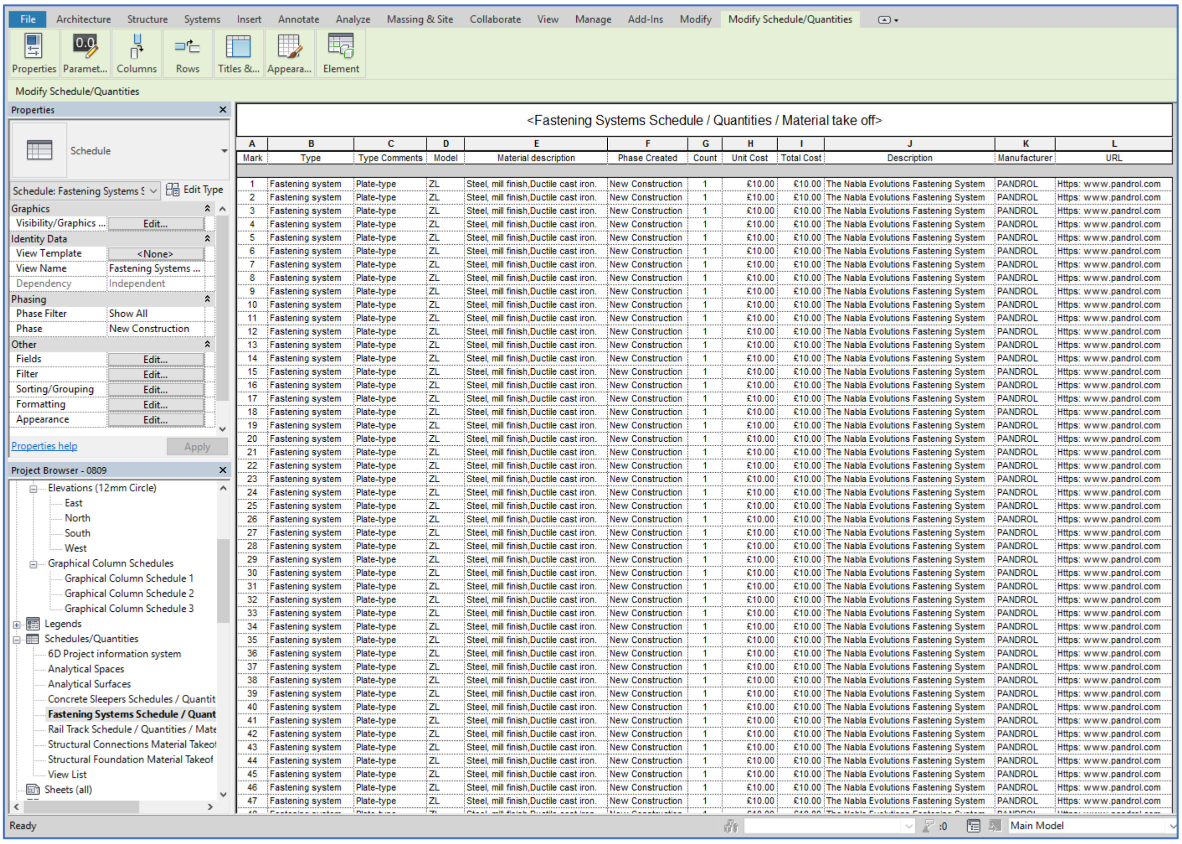


Figure 13: Fastening system material take-off

Revit-2018 can not only take every material off the model and add the corresponding costs into, but also generate the Multi-category Schedule of the project. The Multi-category cost schedule can get the grand total cost of each component, which comprises the cost of material, labour, equipment and other fees, while a separated category cost is only about the material. For instance, the Fastening System Cost schedule is shown in Figure 11.

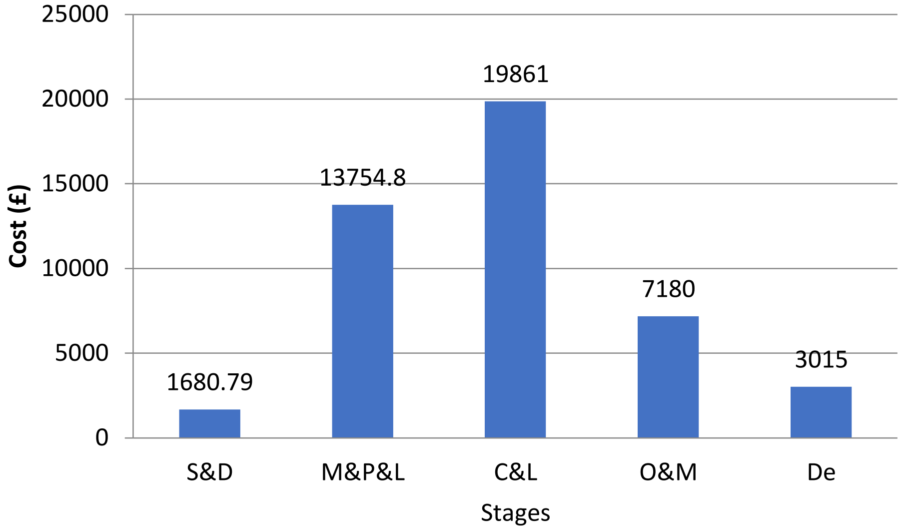


Figure 14: The costs in different stages of the turnout system life-cycle

Based on the cost of each component, it is possible to generate each stage cost in the whole turnout life-cycle. According to Figure 12, it is shown that the cost in the Manufacture & Pre-assembly & Logistic stage and Construction & Installation stage is in the high level with a percentage of 74% of the grand total cost. It indicates that having a good preparation at the beginning and a lean management in the process of these two important phases would be helpful. Shifting this focus to better understand the whole-life cost of assets, where most money is proportionately spent, should make for better decisions upfront in terms of costs (McPartland, 2017).

4.5 Further developments of railway turnout system carbon foot-print and 6D model

Kumar (2015) stated that the major driver of BIM strategy from the Government is reducing costs and decrease the carbon emission of the asset base. The 6th dimension in railway turnout system focuses on carbon foot-print over the whole life-cycle. There are two major elements in the railway turnout system development being considered throughout the life-cycle, which are construction materials and construction machinery (fuel consumption and electricity consumption).

4.5.1 Assessment of CO_2 emissions from machineries

Kaewunruen et al (2015) stated that engineers involved in organising reconstruction project are faced with many considerations regarding the reconstruction practices and project delivery. Inclusions and exclusions are present in this railway turnout system project including:

Table 4: Inclusions and exclusions (Kaewunruen et al, 2015)

item	contents
1	Initial construction earthworks were not considered
2	Ballast track bed is the only track bed considered
3	Fuel emissions and distances travelled from crew vehicles and transport of vehicles to site
4	Energy use to construct the machineries; Financial cost of maintenance activities
5	Track possessions are not considered
6	Labour requirements, including project support personnel and safe working personnel

4.5.2 Assessment of CO_2 emissions from machineries

According to the primary resource records from railway projects in NSW and Kaewunruen et al (2015), type and number of machines used in the railway turnout system life-cycle are estimated as shown in Table 4. Based on the quantity of machines used in different stages, the consumption of coordinated fuel and electricity over the railway turnout system life-cycle are illustrated as follows:

Table 5: Type and number of machines used in turnout lifespan (Kaewunruen et al, 2015)

Item	Planning & Designing	Manufacturing & Pre-assembly & Logistics	Construction & Installation	Operation & Maintenance	Demolition
Office facilities	1				
Staff transportation vehicles	1	1	2	1	2
Front end loaders			2	1	1
16t Excavator			1		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 facilties				1	
Cutting machine					1
Road transportation		1			

Table 6: Planning & Designing stage consumptions

Activities	Fuel consumption (liters)	Unit (l/m)	Electricity consumption(kwh)	Unit (kwh/m)
Investigation on site	30	0.91	N/A	N/A
Designing	N/A	N/A	60.8	1.84

Table 7: Manufacturing & Pre-assembly & Logistics stage consumptions

Activities	Fuel consumption (liters)	Unit (l/m)	Electricity consumption(kwh)	Unit (kwh/m)
Component Production	N/A	N/A	2000	60.61
Turnout pre-assembly	112	3.39	1300	39.39
Turnout Logistics	260	7.88	N/A	N/A

Table 8: Construction & Installation stage consumptions

Activities	Fuel consumption (liters)	Unit (l/m)	Electricity consumption(kwh)	Unit (kwh/m)
Sub-ballast construction	244	7.39	N/A	N/A
Ballast construction	212	6.42	N/A	N/A
Turnout installation	328	9.94	N/A	N/A

Table 9: Operation & Maintenance stage consumptions

Activities	Fuel consumption (liters)	Unit (l/m)	Electricity consumption (kwh)	Unit (kwh/m)	Interval (year)
Rail head grinding	10	0.30	N/A	N/A	2
Ballast resurfacing	10	0.30	N/A	N/A	4
Ballast cleaning/replacement	With renewal	N/A	N/A	N/A	20
Rail replacement	300	9.09	N/A	N/A	10
Switch remote control	N/A	N/A	1000	30.30	N/A

Table 10: Demolition stage consumptions

Activities	Fuel consumption (liters)	Unit (l/m)	Electricity consumption(kwh)	Unit (kwh/m)
Turnout demolition	150	4.55	50	1.52
Concrete sleepers demolition	200	6.06	N/A	N/A
Ballast demolition	260	7.88	N/A	N/A
Sub-ballast demolition	400	12.12	N/A	N/A

As diesel powered and electrical machineries are used in the different stages of the turnout life-cycle. Based on the UK Government GHG Conversion Factors, the assessment of CO_2 emissions from machineries are listed as follows:

GHG emissions (fuel) $=2990\times2.68779=8053$kg

GHG emissions (electricity) =4410×0.28307=965kg

E_u (fuel) = 244 kg/m

E_u (electricity) = 29.2 kg/m

4.5.3 Assessment of CO2 emissions from materials

The embodied CO2-e emissions from materials were estimated using the embodied emissions factors obtained from the ICE (2011) database and Krezo et al (2016) illustrated that embodied emissions factors of railway infrastructures as follows:

Table 11: Embodied carbon emissions from materials in M&P&L stage

Materials	Quantities (kg)	CO_2-e (kg/kg)	EM (kg)	Unit (kg/m)
Concrete sleepers	20367	0.277	5641	170.94
Steel rail	314	2.78	872	26.42
Plastic pads	295.2	3	885	26.82
Fasting systems	628	2.78	2618	79.33

Table 12: Embodied carbon emissions from materials in C&I stage

Materials	Quantities (kg)	CO_2-e (kg/kg)	EM (kg)	Unit (kg/m)
Sub-ballast	64856	0.0051	330	10.00
Ballast	101134	0.005	505	15.30

Table 13: Embodied carbon emissions from materials in O&M stage

Materials	Quantities (kg)	CO_2-e (kg/kg)	EM (kg)	Unit (kg/m)
Steel rail	628	2.78	872	26.42

4.5.3 Total carbon emissions performance and analysis in different stages

Table 14: Carbon Emission Performance

Item	Carbon Emission (kg CO_2-e)	Unit (kgCO2-e/m)	Fraction of Carbon Emission (%)
Fuel carbon emission	8053	244.03	38.3
Electricity carbon emission	1248	37.82	5.9
Embodied carbon emission	11723	355.24	55.8
Total Carbon Emissions	21204	642.55	

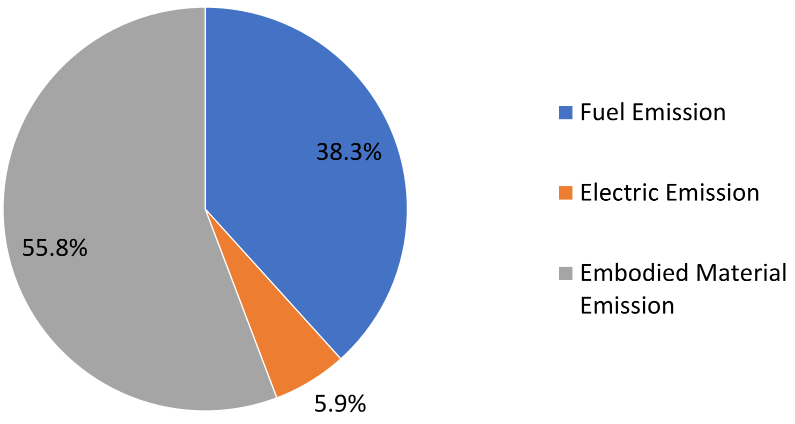


Figure 15: Fraction of the Carbon Emission from different resources

Table 13 and Figure 13 show the quantity and percentage of each resource in the whole life time of rail turnout system. Comparing to the machineries used in special track work reconstruction emitted 15% to 17% of total CO2 emissions (Kaewunruen et al, 2015), it is nearly 27% greater during the whole life-cycle than the pure reconstruction period in this project. As a matter of fact, amount of machinery work is conducted in the stage of operation, maintenance and demolition. Therefore, carbon emission is increased from machineries when it expands to the whole life-cycle.

Table 15: Carbon foot-print in different stages

Item	Carbon Emission (kg CO_2-e)	Unit (kgCO2-e/m)	Fraction of Carbon Emission (%)
Planning & Design	98	2.97	0.5
Manufacturing & Pre-assembly & Logistics	11950	362.12	56.8
Construction & Installation	2942	89.15	14
Operation & Maintenance	3305	100.15	15.7
Demolition	2729	82.70	13
Total	21024	637.09	

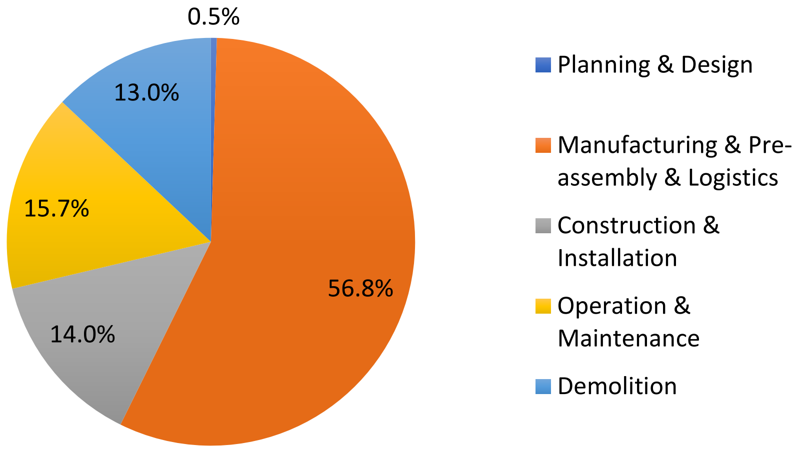


Figure 16: Carbon foot-print fractions in different stages

Figure 14 visualizes that the carbon foot-print percentage varies in different stages of the turnout system life-cycle. The biggest carbon emission occurred in the stage of Manufacturing & Planning & Logistics accounting for 56.8%. It indicates that the turnout system infrastructure as most materials and components are manufactured at this stage. Besides, the key pre-assembly work is also occurred in this phase. Consequently, the carbon emission rises to the highest level over the lifetime. By contrast, as the turnout system differs from common infrastructure projects, the reconstruction stage only includes foundation construction and turnout installation activities, which contains limited carbon emissions with the percentage of 14%. The operation & Maintenance stage carbon emission mainly depends on the frequency of the maintenance in the turnout system project.

5 DISCUSSIONS

BIM of railway turnout system is an application of BIM in the reconstruction phase of railway infrastructure. By creating of 6D BIM modelling at the initial stage of the project, it achieved visualizing a precise graphic dimension, detailed material/component/project information, mature schedule, predicted budgets and sustainable carbon foot-print over the whole life-cycle.

It is important to be taken into account that the turnout modelling is based on the reconstruction phase. The model of this study offers a reasonably complete understanding of 6D BIM of rail turnout system. It is noted that the data for the different components of this model may be variable given the disparate data sources relied on. Nevertheless, this research provides a reference for similar turnout system. In the real project life-cycle, it needs the joint efforts of all stakeholders to build, maintain and share the database, and improvements to the model could be made as better and more specific data sources become available.

GCR (2004) reported that the cost of inadequate interoperability in the U.S. capital facilities industry is estimated at $15.8 billion per year. Egan (1998) found that 30% of construction is rework, 40% of the manpower used on construction sites could be wasted, at least 10% materials are wasted, and over 40% of projects are completed late or over-budget. The above data concludes that better management of project information, better collaboration, better start-up are needed. Therefore, BIM is the best choice. The UK Government (2013) reported that the initial estimated savings to UK construction and its clients is £2bn per annum through the widespread adoption of BIM and is therefore a significant tool for Government to reach a target of 15-20% saving on the costs of capital projects by 2015.

As a consequence, the potential benefits of BIM are that it can reduce the capital cost and carbon emission, decreasing time to practical completion, improved continuity of information, improving whole life asset management, improving consistency in delivery (reduction of errors), improving level of performance and constructability, improving safety, reducing of waste, reducing the consumption of resources (Simpson, 2015).

6 CONCLUSIONS

This research aims to develop a world-first 6D BIM of railway turnout system. This turnout information system is being established over an integrated life-cycle from the planning and design stage to the end of the demolition stage, and it provides six dimensions of information in the project. Besides, this project simulated a life-cycle assessment (LCA) on the basis of shared information. BIM of railway turnout system as a big data sharing platform that enables the planning work to be sequenced logically, efficiently and sustainably, enhances collaboration, allows for feedback before ground and avoids waste, etc. As a matter of fact, BIM makes the railway turnout system more optimised and more intelligent. It is found that this BIM or digital twin can then be used to thoroughly visualize and prioritise maintenance options, promote collaboration among stakeholders, and accurately estimate associated costs and associated technical issues encountered by physical constraints at any pre-determined location. The added benefit of digital twin is its capability to help all stakeholders visualise, and to promote collaboration and co-creation of policy and sustainability improvement solutions among stakeholders, who are often come from different technical backgrounds. In this study, we have enabled BIM to help promote cleaner production and maintenance policy for railway turnout systems that can actually benefit every stakeholder.

With the information technology development, especially the achievement of ‘Internet plus’, BIM will go through sophistication in a wider field. For instance, the integration of BIM and GIS (Geographic Information System) can be applied in urban planning and landscape design, urban traffic analysis, urban safety and intelligent community. It is predicted that the promotion and application of BIM will trigger the second digital revolution in the field of engineering construction. It will facilitate the transformation of the infrastructure industry from factor driven and investment driven to innovation driven in the future.

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NOTATIONS

AEC: Architecture, Engineering and Construction

API: Application Programming Interface

BIM: Building Information Modelling

CDE: Common Data Environment

CO_2: Carbon dioxide

CO_2-e: Carbon dioxide and equivalents, including CO_2, CH_4, N_2O and synthetic gases

EUI: Energy Use Intensity

FM: Facility Management

GHG: Green House Gases

GIS: Geographic Information System

GWP: Global Warming potential

IS: Information System

LCA: Life-Cycle Assessment

LOD: Level of Development

PM: Project Manager

M&P&L stage: Manufacturing, Pre-assembly and Logistic stage

C&I stage: Construction and Installation stage

O&M stage: Operation and Maintenance stage

2D: Two-Dimensional

3D: Three-Dimensional

4D: Four-Dimensional (3D + Schedule)

5D: Five- Dimensional (4D + Costs)

6D: Six – Dimensional (5D + Carbon foot-print)

F_j: the emissions factor for type j material (kg/kg)

EM: embodied CO_2-e emissions per unit track length (kg/m)

E_{ij}: CO_2-e emission of each track section from ballasted track machineries (kg/m)

E_u: CO_2-e emission per metre of track from ballasted track machineries (kg/m)

N: total number of material types used in track construction

QM_k: quantity of material k required per metre of track construction (kg/m)

QiCi: quantity of fuel and eletricity per metre of track construction (kg/m)

T: track length processed in a renewal maintenance project (m)