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Digital Twin for Sustainability Evaluation of Railway Station Buildings

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The railway station is a primary asset of public transport systems and plays a crucial role in urban modernization. Most existing railway stations in the UK is historic and have been operated for many years. Maintenance and reconstruction are common concerns in the public railway industry, and clusters of information pertaining to this maintenance must be managed appropriately for effective outcome. Digital twin or BIM (Building information modeling) is a term frequently employed in the construction industry nowadays, because of its ability to provide wider and faster access to comprehensible and integrated information. A digital twin or a BIM is not only a tool, but also a process that can help to make changes in construction industry, which has remained unchanged for hundreds of years. This paper discusses a specific BIM application within the context of railway station buildings using a Revit-based simulation of construction work for King's Cross station in London. The paper highlights the adoption and transformation of 3D model of the King's Cross station building into a 6D building information model. The 6D model contains a time and cost schedule with carbon emissions calculation, and renovation assumptions using Revit. The outcome of this study can provide construction participants with reasonable guidance of BIM adoption on railway station projects that can be used for planning, designing, and operating an economic and environmental efficient construction project.

Keywords: railway station building, digital twin, BIM, revit, BIM adoption on existing buildings, green construction

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INTRODUCTION

Construction is one of the most typical cooperative job, and information must be exchanged and shared between construction participants. Traditional paper-based construction methods has been considered as one of the major cause of project delays, cost overruns, and other construction project problems (Davidson and Skibniewski, 1995). However, Building Information Modeling (BIM), a widely discussed term within the construction industry worldwide is broadly anticipated to provide huge technological and procedure shifts in the Architecture-Engineering-Construction (AEC) industry (Noor et al., 2017). The UK government has stipulated that beginning in 2016, all public sector projects (regardless of size) must make use of fully collaborative 3D BIM technologies and processes. This policy has inspired intense interest in BIM technology within the UK and elsewhere (Kumar, 2015).

The railway station is a type of public facility that offers passengers access to trains and other transport systems. Within the context of a city plan, such stations also act as concentrations of facilities as well as various accumulation of assets and open spaces. Because of the various objectives and complexities presents buildings in the UK face widespread aging and reconstruction problems, appropriate information and a well-produced management philosophy should be applied to ensure a successful outcome.

This paper primarily focuses on the investigation of an intermediate railway station's design and construction processes in tandem with maintenance management based on BIM techniques and Revit software. These areas of interest will be considered via a simulation of construction work for King's Cross station, one of the busiest railway stations in the UK. Renovation management and environmental effect will also be discussed. Although, the scope of this study is limited to BIM adoption in the context of King's Cross station, the process and methodology presented below will provide a positive example of the potential of BIM adoption in railway station construction. This study into BIM applications will converge information production with sound engineering judgement and design, as well as provide a reasonable guidance, which can be used for planning, designing, and operating a more economic and environmental efficient model comparing to traditional construction outcomes.

LITERATURE REVIEW

Immense effort has been devoted to facilitate the collaboration within AEC industry. Much of this attention has been given to Building Information Modeling (BIM) technology, which has helped engineers to generate value thought during early collaborative work (Olatunki and Sher, 2009). In last few years, many practices and papers have demonstrated the benefits of BIM technology and its facilitative effects within the construction process. In 2014, Faghihi et al. demonstrated a novel approach to the development of construction sequencing for the installation of project elements by retrieving enough information from BIM (Faghihi et al., 2014). In 2015, Trebbe et al. provided practical evidence for the advantages of 4D CAD model application within the construction process based on a case study of a major railway station renovation project in the Netherlands (Trebbe et al., 2015). In 2015, Lin proposed a web-controlled Construction BIM-based Interface Management (ConBIM-IM) system, which is capable of aiding engineers in improving interface information sharing and efficiency tracking in construction projects (Lin, 2015). In 2017, Angel et al. presented a modification of IDM (Information Delivery Manual) methodology and LOD approach of risk assessment of BIM adoption (Lu et al., 2015). In this section, the author presents several papers specifically related to BIM adoption among railway station projects in order to discuss the feasibility and significance of this study's project.

Firstly, relevant researches about BIM technology information and railway stations are reviewed. In 2012, Azhar et al. presented an overview of BIM and the application of BIM technology within the project life cycle. The benefits of BIM application were summarized as follows: possible hazards and mitigation plans can be developed; up-to-date information can be reflected in a timely manner for building operations and maintenance; and the use of BIM technology in facility management (FM) prevents loss of life cycle costs. For public facilities, research suggested that 85% of life cycle cost is incurred following construction completion. This paper demonstrates the potential benefits of BIM application in railway station construction, both for construction management of ongoing construction projects and facility maintenance of existing facilities (Azhar, 2012). Next, in 2016, Kaewunruen et al. presented a paper discussing the current circumstances and significant challenges associated with transportation and transit systems. The authors pointed out that the construction, operation and maintenance of transportation facilities are substantial sources of greenhouse gas emissions, even though railway transportation has become the most environmentally and economically efficient logistic system available to date. The authors also pointed out that today's infrastructures face aging problems and argues risks and potential societal consequences may occur without appropriate monitoring and management. It is suggested that the twenty first century's engineers will be primarily responsible for the modernizing and management of fundamental public assets that support civilization. Under these circumstance, BIM may prove a good solution for providing systematic estimates and management of greenhouse gas emissions (Kaewunruen et al., 2016). Next, a literature review by Volk et al. (2014) considered over 180 academics and applied publications that focused on existing buildings was conducted. The results of this paper indicate that studies in the engineering industry focus on buildings which are new or recently completed and have an available building information model, rather than on existing buildings without BIM information. However, the benefits and functionalities of BIM application within maintenance and deconstruction work on existing buildings are numerous. These benefits include enhanced project management, risk mitigation and onsite monitoring (Volk et al., 2014). Most existing railway station buildings were built without BIM information models. It is essential to produce information models of railway station buildings that consider potential reconstruction as well as maintenance and management work.

Next, papers about specific BIM technologies and applications are discussed. Angel Gigante-Barrera et al. presented an IDM based framework for risk mitigation using Level of Development (LOD) with railway turnout systems as the model processes. This paper's main objectives were to (1) investigate the association between railway turnout risk management and BIM design processes and (2) study the creation of an LOD driven BIM database. The authors modified the IDM methodology focused on a former IDM guide that centered on the process map stage. Besides, various LOD constructs for its implementation within the IDM standard were studied. The authors also stated that after establishing the LOD implementation process, the link preventing BIM risks can be set (Lu et al., 2015). Next, in a paper considering BIM tools for carbon calculation, research that developed a tool for assessing carbon footprints within construction via BIM technology was presented. Daily Energy Use (CFeu) in BCF design phase (BCFd) was selected as example to calculate the carbon footprint consumption from lighting. The evaluation process used a BIM model and calculated carbon disclosure with Revit API processing. Unlike previous carbon footprint calculation methods, which can only evaluate after a design case is finalized, the authors argued that CFeu tool can instantly recalculate performance after modifications to design cases (Lu et al., 2015). This means BIM based carbon footprint calculation can provide real-time user feedback. Finally, Krezo et al. (2016, 2018) carried out a field-based information collection study on plain-line ballasted track renewal projects. Results showed that rail infrastructure maintenance extended facility lifespans and helped reduce carbon emissions. In this paper, specific greenhouse gas (GHG) emission estimation methods were introduced to reduce the uncertainties and providing reasonably accurate estimate (Kaewunruen et al., 2014, 2015, 2016). The estimation methodology mentioned in this paper can aid in construction carbon emission estimation and give guidance of carbon emission calculation for the King's Cross station project.

Finally, this literature review considers papers studying BIM adoption in the context of railway station projects. In a research article by Bashar and Syed, specific modeling for XiaMen station, China was discussed. This research team advocated that even though BIM adoption is now limited to normal building construction, the technology has great future potential within railway station construction. The researchers checked standard planning and designing rules and prepared 3D models of separate station elements; the entire modeling process was systemized as a Revit-extension tool. From the completed 3D model of the proposed railway station, they concluded that building information modeling technology is capable of automatic document generation and coordination, as well as revitalizing the layout process of intermediate railway stations (Noor et al., 2017). A research paper by Tian et al. presents a case study of metro project construction by considering the Hedong metro station located in Guangzhou, China. The authors of this paper adopted a range of methods, including combining unique paramedic 3D models, constituting construction schedules and a 4D model by connecting each 3D component with a unique regional attribute, as well as developing an order sheet method to control the construction process and ensure comprehensive construction management. After application, results showed that this system successfully reduced construction costs, shortened construction time, and guaranteed construction safety by enabling real-time conversation and information exchange during construction process (Tian, 2015). These results demonstrate the positive potential of BIM application in facilitating effective, high-quality construction.

After considering all the papers presented above, this researcher has concluded that BIM application is growing with gradually importance in the AEC industry and can play a crucial role in enhancing the whole life cycle of construction work. However, literature about application of BIM technology on existing buildings, specifically railway station buildings, is still limited. While BIM adoption on construction management is in great demand because of its efficiency of information gathering and innovation in asset management decision making and collaboration methods. Based on the above findings and research methods applied in relevant papers, this author will discuss specific criteria of BIM application in railway station building construction and management by creating a modeling simulation of King's Cross station in London. The selected methodology and project outcomes will be presented at length below.

METHODOLOGY

In this section, the methodology adopted for this project is presented. In order to develop a BIM-based railway station building project, the author conducted a modeling simulation of King's Cross station. Building information modeling can provide a powerful platform for visualizing workflow in control systems (Olatunki and Sher, 2009), and the technology will also prove a suitable solution for improving construction management procedures. Therefore, alongside modeling procedures, construction management improving systems will also be discussed. The project's methodology is discussed in three sections: (1) understanding BIM and BIM tools, (2) 3D modeling of King's Cross station building via selected software, (3) information modeling simulation including time schedule, cost estimation, carbon emissions and renovation simulation. The first section identifies the overall purpose of BIM technology and specific BIM software as well as the adoption of BIM on railway station building project. The second section lays the foundation of this study; the collection of design data and use of Revit to simulate a 3D model of the King's Cross station. Finally, a so-called 5D BIM model is created via the addition of building information, Including construction schedule and cost estimation. Carbon emissions from the construction process and renovation simulations will also be investigated to achieve a 6D BIM model. Most available researches about BIM adoption nowadays focus on newly built construction projects with 5D information models. The carbon emissions calculation and renovation management method attempted in this study will provide fresh potential of BIM adoption on railway station building projects with an environmental efficient model. The details of each of these sections are explained in greater detail in the following sub-sections.

Understanding BIM and BIM Tools

The National Building Information Modeling Standards (NBIMS) committee of the USA defines BIM as follows: "BIM is a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life cycle; defined as existing from earliest conception to demolition. A basic premise of BIM is collaboration by different stakeholders at different phases of the life cycle of a facility to insert, extract, update, or modify information in the BIM to support and reflect the roles of that stakeholder" (NBIMS, 2010). As is clear from the definition above, BIM is not only about software, but also processes. BIM adoption requires not only the application of 3D models, but also significant changes in workflow and project delivery processes (Hardin, 2009). Technologically, BIM can be introduced as a simulation process comprising 3D model project elements with links to information pertaining to project planning, design, construction, or operation

(Azhar, 2012). From a process perspective, BIM can encompass all aspects, disciplines, and systems within facility with a virtual model that enables accurate information collaboration between team members (Carmona and Irwin, 2007).

Compared to traditional CAD method, there are a number of software products available that can convert 2D design data into a 3D model. This BIM software can provide a comprehensive view of any side of the structure or particular design element and also evaluate potential conflicts and omissions among design elements. Several software products are recognized by the industry, including Revit by Autodesk and Bentley® Systems and Graphisoft®. For this project, the author employed Revit to conduct 3D modeling. Revit Architecture is a software purpose-built for BIM to offer automatically ordinated change throughout the project. It is designed based on the viewpoint that "a change anywhere is a change everywhere" (Blanco and Chen, 2014).

3D Modeling of King's Cross Station Building

King's Cross station in London is one of the busiest railway stations in the UK. The station is located at the boundary of the city of London, close to the end terminal for the high speed railway link to Paris and Brussels (Holgersen and Haarstad, 2009). The location site of the station can be seen in **Figure 1**. In this paper, the author created a 3D model with Revit based on 2D drawings published on ArchDaily (2012). Modeling components, such as architecture components (floor, stair, and interior wall) and structural components (beam, column, and outer wall) must be integrated to complete 3D modeling. As for the semi-circular metal roof structure, the author first used AutoCAD first to sketch the structure and then converted the structure to Revit to complete the model.

Information Modeling Simulation

Next, to create a BIM information model, the 3D models were linked with building information. 5D BIM can be expressed as the combination of three essential element sections: the 3D (three-dimensional) project's data, time-related information (as the fourth dimension), and cost-related information (as the fifth dimension) (Popov and Joucevicius, 2009). Generally, the concept of 5D Generally, a 5D project is the expression of a 3D model in time and calculation of cost during its lifecycle (Migilinskas and Ustinovichius, 2006). The King's Cross station is a completed facility, and the original design data is too old to have practical significance. For this reason, the author made several assumptions pertaining to cost and time related information and placed emphasis on the application process of BIM technology in railway station buildings. The combination of 3D model, time-related and cost-related information was information achieved via the order sheet method, which is order sheets consist of schedule and resource information and related 3D components, construction guides, materials and equipment, workers, and so on (British-gypsum, 2012). Because this King's Cross railway station project is a simulation that lacks real owners, contractors, or workers, the benefits of BIM on construction management process can be neglected without mention. While the order sheet method proposed in this paper is a simulation that showcases the advantages of BIM technology in construction process control and management, significance of BIM adoption on construction management can be reflected well. Order sheets are typically completed by the contractor, who supplies construction information, and then transferred between engineering consultants, contractors, and workers. Hence this method requires collaboration between team members and is useful for real-time tracking of onsite work and facilitating communication between construction participants. Order sheets also guarantee efficiency to construction site, as changes on site can be automatically integrated into the BIM data repository. The detailed process of order sheet method will be presented in **Figure 2**.

To ensure sustainable infrastructure, construction projects these days must consider environmental impacts such as climate change and air pollution as major decision-making criteria (Kaewunruen et al., 2016). Researched shows that infrastructure construction and related activities are responsible for over 20% of carbon dioxide (CO_2) emissions. These results demonstrates the importance of the systemic estimation and management of greenhouse gas emissions over a project's life cycle (Kaewunruen et al., 2016). In this paper, the author conducts the carbon emission analysis. Carbon emissions produced at construction site are split between initial construction and earthwork, material production, material transportation and waste removal, machine manufacturing, and so on. Because of the difficulties associated with actual construction practice estimation, this paper's carbon emission calculation primarily addresses the gas emissions of material production and carbon emissions according to different construction production in order to demonstrate the framework for 6D BIM of a railway station.

Carbon emissions associated with construction material consumption are calculated by a general carbon emissions equation given in DOE (2014):

$$\mathrm{EM} = \sum \mathrm{EFiQMi}(\mathrm{i} = 1 - \mathrm{N}) \tag{1}$$

where

i is material number.

N is the total quantity of material types applied in railway station building construction.

EFi is the embodied carbon emissions factor for type i material (kg/kg).

QMi is the total weight of material i required in railway station building construction (kg).

The carbon emissions of other construction practices are estimated based on materials published by BIS (2010). These material's carbon emissions factors and carbon emission estimation materials are expressed and explained in the paper's **Appendix**.

Renovation Management Using Revit

A great variety of ICT-related researches, working process development, data exchange methods, and software applications are focused on new buildings, yet reconstruction related design processes and management discipline have not been comprehensively studied (Penttila et al., 2010). This vacancy

FIGURE 1 | Location site of King's Cross station (Google Map, 2018).

of study in this area leads to great demand and significance of relevant researches. It is recommend that geometric 3D-modeling, tachometry-based measurements, 3D laser scanning and many other methods can be considered for reliable renovation modeling work (Azhar, 2012) in order to prevent unnecessary loss and damage. There have been many accidents on public facilities in the history because of lack of proper management measures. In 1987, a major fire accident at King's Cross station caused extraordinary economic loss, society panic, and loss of life. The cause, which can be easily pointed out within proper asset management strategy, was investigated to be the lack of cleanliness underneath fire preventing escalators (Crossland, 1992). Under such circumstances, fire and terrorism prevention within public facilities are vital to building renovation plans. In this study, fire stopping and smoke control measures were applied to the BIM model with simulate of BIM building renovation modeling. During a fire incident, fire and smoke primarily spread between gaps in walls and ceilings, via fire non-resistant weaknesses in the structure and by traveling through windows and external surfaces to re-enter at upper levels. While fire prevention and smoke control systems assist in reducing the spread rate of fire and smoke inside a building in order to give occupants time to escape. In this project, fire prevention design was applied by three basic options: (1) installation of fire doors and windows, (2) construction of internal double glazing curtain wall, and (3) insulation of cavity walls with fire barrier. This renovation modeling was carried out using Revit phasing function, which can control the display of elements based on their phase status to assign demolishment work, as illustrated in **Figure 3**. After completion of renovation modeling, the cost estimation, and carbon emission for each option were compared. These estimates are presented in section Results and Discussion.

RESULTS AND DISCUSSION

Based on the approach mentioned above, a BIM-based construction design and management system for railway station building was developed in this study. The logistic consists of a 3D model of King's Cross Station building as well as information models with time and cost schedule in the form of order sheets, and renovation simulation using Revit phasing function. In this section, the author presents the project results in graphics and finally gives some discussion upon the result.

Project Results

The BIM data depository is responsible for providing the various project information for this railway station project, including external and structural information and corresponding technical information. BIM is a solution for construction data exchanging and updating. The results of BIM application on railway station

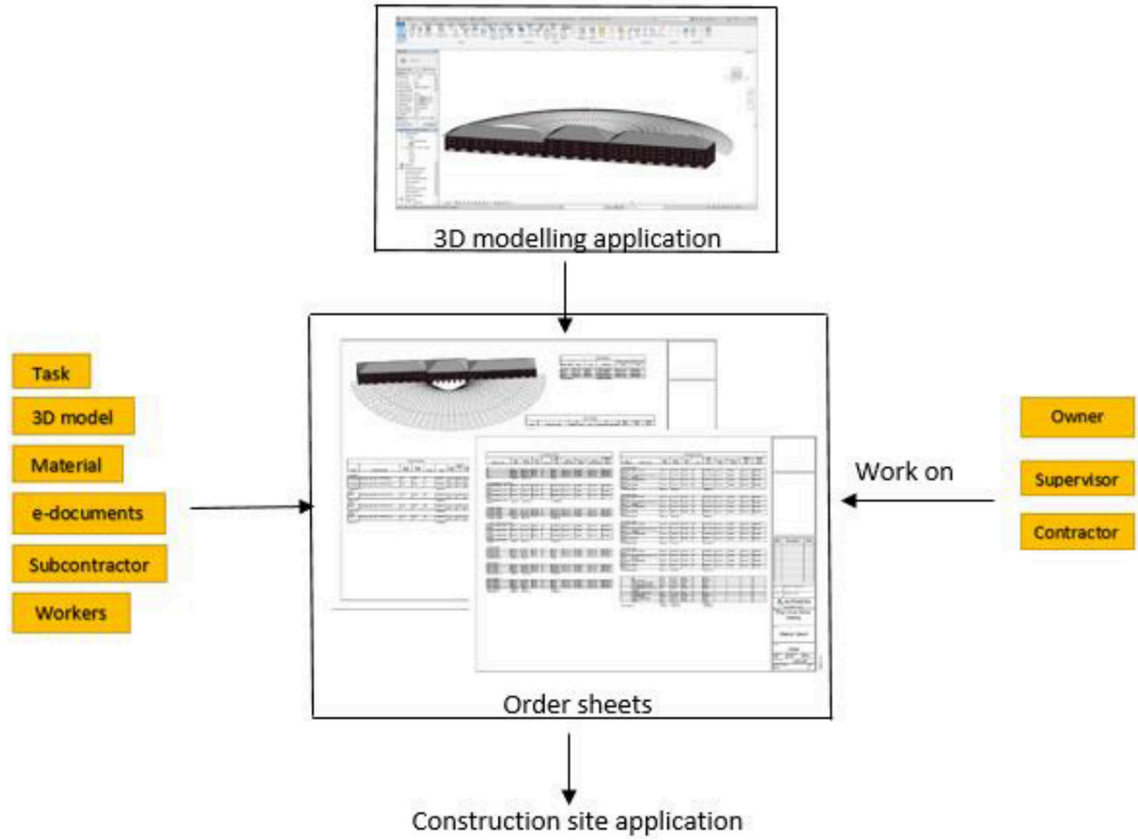


FIGURE 2 | The order sheet method for construction process control.

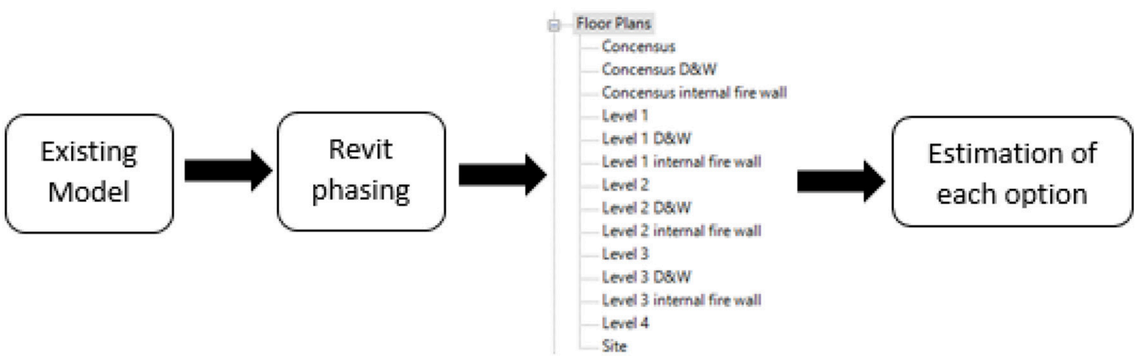


FIGURE 3 | Project renovation using Revit phasing.

building, as seen in this project, demonstrate BIM adoption's significant benefits to construction design, management, and maintenance work.

A 3D model of King's Cross station was constructed based on design data mentioned in methodology section above. When drawing this 3D model, three work phases—external architecture, structural components and interior components—were intended. External architecture included overall external components, such as walls, floors and roofs. This section was built based on 5 levels of building height. After the architecture components were added, structural components, such as beam and column systems were integrated to create a structurally-complete model. Finally, interior components such as stairs, windows, and doors completed the model. After finalization of the 3D model, information modeling, which is the essential aspect of BIM technology, was conducted. Time schedule and material takeoff, including cost estimates, delivery, and order estimates were calculated. To synthesis a 5D model, construction

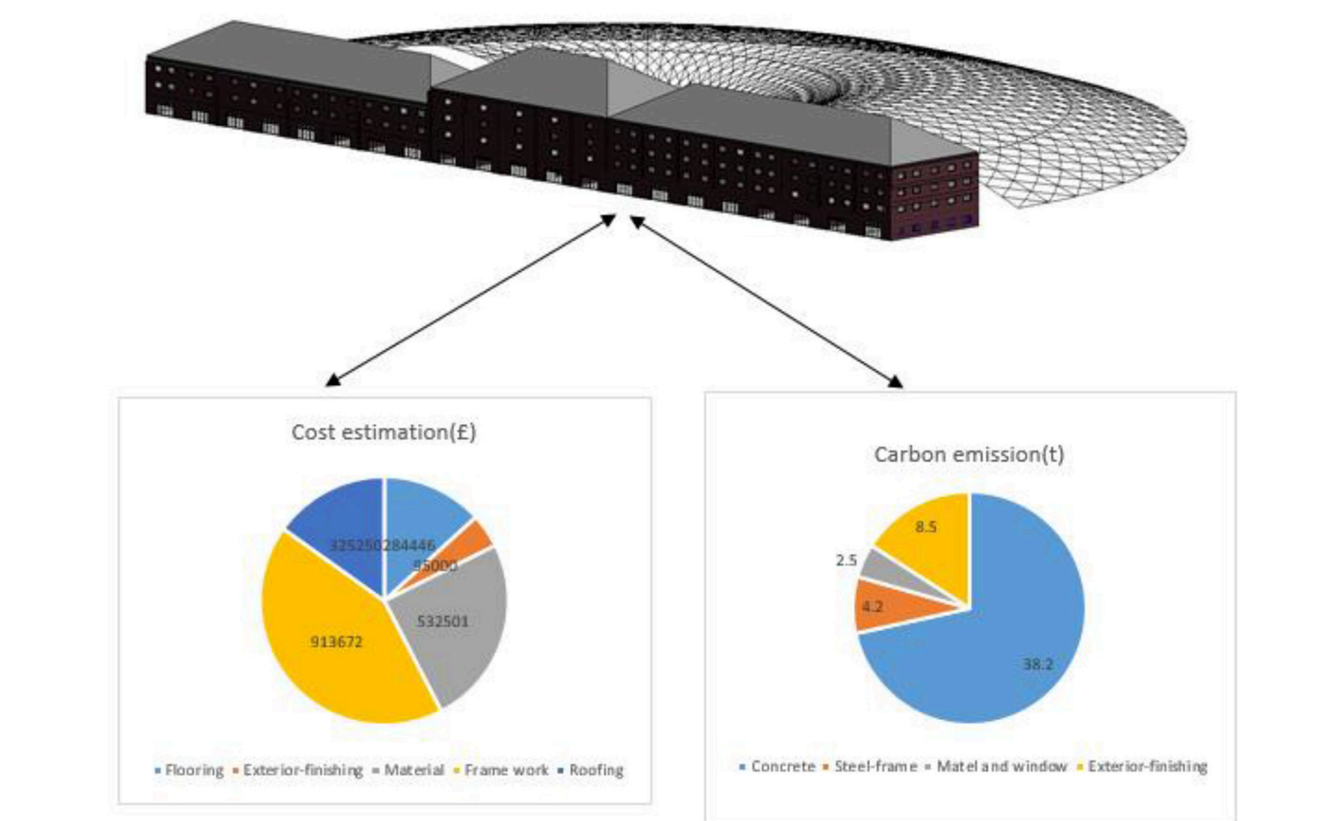


FIGURE 4 | Project cost estimation and carbon emission results.

simulation, schedule, and resources management information were gathered into order sheets. Unlike traditional paper-presented or e-documented construction methods, a BIM-based design process enables a timely and changeable model. Accurate process data can be collected and delivered to each BIM data repository. This makes collaboration and data exchange between construction participants easier, more efficient, and consistent. Is also allows for accurate and timely analysis of resource consumption. This project's results show that BIM technology can aid in project cost reduction, as well as quality and safety control, producing a cheaper, safer, and less time-consuming construction process. The project divided cost estimation of construction practices into five parts: flooring, exterior-finishing, material, frame work, and roofing. Estimation for each of these parts were £284446, £85000, £532501, £913672, and £325250, respectively. Carbon emission calculation was divided into concrete production, steel-frame, metal and window, and exterior-finishing. Each part's emissions were calculated as 38.2, 4.2, 2.5, and 8.5t, respectively. A 3D model with cost estimation and carbon emission calculation results can be seen in **Figure 4**.

Alongside construction work, maintenance and operation of constructed assets are essential functions of today's AEC industry. However, due to difficulty of (1) data capture without existing BIM, (2) update and maintenance of BIM information, (3) handling of uncertain data, objects and relations (Volk et al., 2014), BIM application on existing buildings has not been spread enough. In this project, a traditional building renovation simulation was carried out with a complete model using Revit phasing function. The renovation work of each level was divided into different phases, and then apply phase filters were applied to views and schedules to illustrate the project during various work stages. The phase filter can be applied to control the display of components depend on their phase status, whether it is new, existing or demolished. Each phase of demolished elements can be changed to a unique color similar to process schedule to make renovation work easier to control. Because all equipment is already associated with various information, such as model names, model numbers, product types, performance data, and material takeoff, changes of the information model resulting from renovation work can be automatically updated. This feature once again demonstrated the advantages of BIM technology in construction management work.

The three options selected as part of renovation work are (1) installation of fire doors and windows, (2) the construction of internal double glazed curtain walls, and (3) the insulation of cavity walls with installation of fire barriers. In the first option, 82 of FD60 single doors, 13 of FD 60 double doors and 317 of double glazed windows were designed to be retro-fitted within the building. In the second option, 1,507 m^2 of double glazed curtain walls were designed to perform as fire stopping internal walls. The curtain wall model selected was fire-resistance tested in compliance with the ASTM E2307 and the time-temperature curve of the ASTM E119 (Rosa and Lu, 2016). In the last option, Rock-wool-based insulation was employed as the cavity wall insulation material with TCB cavity barriers produced by a company called ROCKWOOL (Rockwoll, 2015). This method offers fire protection for timber frame and masonry cavity walls via concealed voids that prevent the spread of fire and smoke. According to Energy Saving Trust, cavity wall insulation is also an efficient strategy for saving energy and lowering life-cycle carbon emissions. Each option was transferred to model information in Revit through different phases. Costs were estimated and carbon emissions were calculated from the activities in each life cycle stage, and the results can be seen in **Table 1**. The information for calculations is listed in the **Appendix**. The total cost for each option is estimated from the costs of materials and the estimate of activities involved for installation of each option.

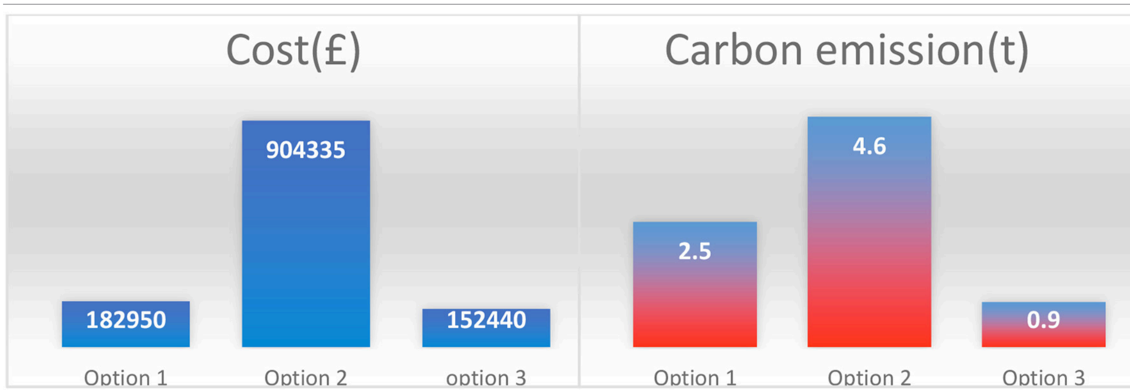
From the results, it is evident that Option 3 (the insulation of cavity walls with installation of fire barriers) is the cheapest and incurs the lowest carbon emission rate among all options. However, the actual performance of these options require further investigation, such as analysis of carbon emissions and cost-efficiency over whole life cycle. Still, this results should be emphasized as proof of advantages of BIM application because of the easiness of automatic information processing.

Discussion and Critical Thinking

In addition to the advantages discussed of BIM, many associated risks and barriers must be considered prior to its implementation. First of all, BIM adoption lacks a professional standard for model incorporation and management by multidisciplinary teams. As a result, BIM interoperability may not always prove efficient. This lack of currently available standard protocols can result in inconsistencies and inaccurate models. In additions, the ownership of BIM data can also incur legal and contractual risks occurs. Ownership and protection of BIM data has proven difficult to determine under existing copyright law. There are also contractual issues tied to responsibility for inaccurate modeling or data entry control (Ashcraft, 2009). Because taking responsibility for updating building information data and ensuring its accuracy involves great risk, requesting a complicated BIM model often translates to higher project cost (Azhar, 2012). Collaborative, integrated project delivery contracts may effectively address such risks by allowing the risks and rewards of BIM application to be shared by project participants (Azhar, 2012).

The model presented in this paper has a few limitations that may affect its accuracy of material accounting. Accuracy of a model can be expressed as the level of development, or it's LOD, which is an important factor that can be seen as a qualification to prove reliability of BIM models (BIMForum, 2013). Currently, LOD 300 or LOD 350 are generally required in most typical stages for a building model (Solihin and Eastman, 2015). Between which, LOD 300 requires specific systems, objects or assembly in connection with quantity, size, shape, location, and orientation with optional attached non-graphic information. While LOD 350 needs requirements for connections with other buildings systems (Solihin and Eastman, 2015). Because this model lacked accurate design data for the project's building and surrounding area, the accuracy of the model cannot be wholly guaranteed. The difficulty of data capture and handling are common issues engineers face when working with projects that require renovation or redevelopment of existing buildings, because there are not enough existing guidelines, models nor inventory mechanisms (Penttila et al., 2010). Besides, incapable interoperability is also a major obstacle in BIM data exchange, and challenges will arise from interoperability within BIM models over the course of long lifetimes of buildings and infrastructures. Mistakes and errors will result from rapidly developing BIM models that outpace data collection (Volk et al., 2014). As for this King's Cross station building model, despite limited design data and connection with the surrounding area, we have made the model as detailed as possible. The project's primary positive influence is on BIM adoption among railway station building projects. The potential issue with LOD has been minimized

TABLE 1 | Cost estimation and carbon emission calculation of three options.



and the field verification during operations will eliminate the problem.

CONCLUSION

This paper investigated BIM adoption for a railway station building project that can provide positive potential of this technology on existing buildings and railway station projects specifically. BIM is a technology with growing demand in construction field because of its significant improvement of information management method. However, due to difficulty of information capture on existing buildings, 6D BIM model with carbon emission calculation and renovation simulation attempted in this paper is still hard to be seen. Key methods of this paper included the integration of 3D models, the combination of construction information (including construction schedules, cost estimations, carbon emissions, and renovation simulation) using the order sheet method to develop a 6D BIM model. The project simulated King's Cross station in London based on construction management methods and also discussed the limitations and risks of applying BIM technology. Although this study is limited to King's Cross station, its findings, to a degree, provide an example of BIM adoption on railway station buildings or existing buildings. In the future, the system will require revision according to changes and improvements in application to achieve an efficient model over whole life cycle. The outcome of this study can provide construction participants with reasonable guidance of BIM adoption on railway station projects that can be used for planning, designing, and operating an economic and environmental efficient construction project. The use of BIM for new infrastructures can enhance the intelligence of the infrastructure systems, by

- locating sensors that can inform the real-time condition of the infrastructure;
- optimizing the construction processes and logistics that reduce both costs and carbon footprint; and,
- visualizing the novel design that can increase quality, movement or flow, safety, and comfort for the end users of the interconnected and interdependent infrastructure systems.

AUTHOR CONTRIBUTIONS

SK and NX developed the concept; SK developed the sustainability criteria; NX developed BIM and data flow; SK verified the outcome; SK and NX wrote the manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fbuil.2018.00077/full#supplementary-material

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