Digital Twin Aided Sustainability and Vulnerability Audit for Subway Stations

Sakdirat Kaewunruen [1,*], Shijie Peng [1] and Olisa Phil-Ebosie [2]

[1]   Department of Civil Engineering, School of Engineering, The University of Birmingham,
       Birmingham B15 2TT, UK; SXP808@alumni.bham.ac.uk
[2]   Transport for London (TfL), 5 Endeavour Square, London E20 1JN, UK; OlisaPhil@tfl.gov.uk
*   Correspondence: s.kaewunruen@bham.ac.uk

Abstract: Digital twin (DT) or so-called 'building information model (BIM)' has brought great revolution to the current building industry. Its applications to life cycle management of buildings and infrastructures can further increase the social and economic benefits. As a complete information model, a digital twin integrates the information of a project from different stages of the life cycle into a model, in order to facilitate better asset management and communicate through data visualizations with participants. This paper unprecedentedly introduces a digital-twin aided life cycle assessment to evaluate a subway station. Dadongmen subway station in Hefei was used as a case study. This new study benchmarks the cost estimation and carbon emission at each life cycle stage of the project. The cost in the construction stage of the project is the highest, accounting for 78% of the total cost. However, the amount of carbon emissions in the operation and maintenance is higher than the amount during the production of building materials, accounting for 67%. Among them, concrete only accounts for 43.66% of the carbon emissions of building materials, even though concrete was mainly used for constructing the metro station. Steel bar and aluminum alloy have carbon emissions of 29.73% and 17.64%, respectively. In addition, emerging risks of the subway stations can be identified. The digital twin has been used to illustrate vulnerability and potential solutions to emerging risks, and to assess the suitability through life cycle cost and carbon footprint. This initiative is relatively new to the industry. The new insight into life cycle assessment or LCA (especially carbon footprint over the life cycle) integrated with digital twin applications will enable sustainable development that will enhance resilience of metro railway systems globally.

Keywords: subway station; metro station; BIM; digital twin; life cycle analysis; carbon emission; sustainable development

1. Introduction

At present, the subway is one of the most popular means of urban transportation for people to travel because of its diverse positive advantages, such as being safe, fast, environment-friendly, and at a low price. Therefore, a subway has been an important part of urban transportation systems. The subway network has been expanded rapidly in China. However, with the rapid development of built environments, a large number of natural resources have been consumed by increasing non-renewable energy, depleting fresh water and natural materials, and emitting greenhouse gas emissions significantly. In general, carbon emissions are incurred during construction, operation, maintenance, and dismantlement of a building. Additionally, the incurred carbon emissions will cause the greenhouse effect and threaten the living environment of human beings. During a construction project's whole life cycle, there are many participants and stakeholders; and, relevant information generated is of complex types, diverse forms, and large amount. As a result, information communication

in the management process is traditionally not smooth, resulting in serious information loss throughout the whole life cycle of the construction project. Cooperation, visualization, and the data sharing process between the contractors, stakeholders, and also the customer is one of the most influential factors in the construction process. The purpose of data collection is to forward convincing and credible answers of questions through data analysis and visualization [1]. A digital twin (DT, which is commonly used for infrastructures) or so-called building information modeling (BIM, which is traditionally used for building structures) is a digitization technology currently applied and adopted in the construction industry. Due to its characteristics of overcoming complexity and difficulty in data management, it has been widely used in construction engineering and project management [2].

In recent years, the advantages of BIM for building projects have become increasingly obvious, since BIM could overcome delays in construction, increased costs, inconvenient coordination and communication, improving quality and safety in engineering construction. However, equally obvious is the fact that carbon footprint and energy consumption have not been thoroughly determined by BIM due to the limitation of data available and supporting software feature. BIM technology has thus been conventionally used to simulate the construction project in the virtual environment to improve the digitization and visualization of the accurate virtual model of the buildings. On this ground, BIM currently plays an important role in the architecture, engineering, and construction (AEC) industries [3]. The BIM Industry Working Group reports that British government believes that BIM technology can be successfully applied in the life cycle of construction projects and bring benefits because it could reduce cost and waste by modifying design parameters and other operations once the actual construction processes change [4]. In addition, there are also perfect legal systems to manage BIM in foreign countries so the British government construction strategy published that all of the UK's public projects are required to adopt 3D BIM fully to enhance stakeholders' collaboration by 2016 [5]. However, it is noted that the key goal and functionality of required BIM in practice is simply to enhance data communication and stakeholder collaboration (which can be referred to BIM Level 1.0).

Current development and advancement of a BIM (for buildings) or so-called a digital twin (for other types of infrastructures) is limited by data availability. Most applications of a digital twin are based on data collaboration and design visualization in order to communicate better among stakeholders. This is the BIM Level 1.0 where the 3D model has been used with a variety of information layers. In practice, the level of details (LOD) can be adopted as an agreed standard reference to assure that data format and structures among relevant stakeholders (e.g., designers, engineers, CAD specialists, architects, surveyors, etc.) can be shared and correlated within a digital twin framework. Nevertheless, current adoptions of a digital twin are still based on BIM Level 1.0. The lack of key information and relevant essential measurement data has restricted the development and advancement of BIM Level 2.0 and Level 3.0 where other dimensions of key information are critically required. This deficiency in practice has led to a new initiative in this study to demonstrate the use of a digital twin to further assess sustainability from life cycle perspectives of costs, energy, and carbon footprint, and then to help identify the potential solutions towards emerging risks stemming from the vulnerability of infrastructures exposed to multi hazards.

The construction of a subway station is a complex process, as the construction of a subway station often encounters challenges such as long construction periods, complicated construction, and difficult project control. The purpose and scope of this paper is to use a digital twin or BIM technology via Revit software to carry out simulation research and analysis on a subway station's design, construction process, and maintenance management. This can be reflected in the simulation using design and construction processes and data obtained from the Dadongmen subway station in Hefei, China. This paper also determines the life cycle costs and carbon emissions produced by this project and analyzes the transformation management and environmental impact. Based on previous studies on public transportation buildings, this paper adopts a BIM software to conduct digital simulation analysis on the Dadongmen subway station as illustrated in Figure 1, which could build a pathway to future research on BIM applications in other subway station buildings. The outcome of this study will

support decision making processes in order to prioritize design and construction activities of subway stations to enhance the sustainable development goal (by striking the balance among life cycle cost, carbon footprint, societal needs, and other consequences and capacities). In addition to this study is the use of the digital twin to identify potential and assess potential solutions to emerging risks stemming from multi hazards and threats. This insight will help underpin a vulnerability assessment for improving metro infrastructure resilience.
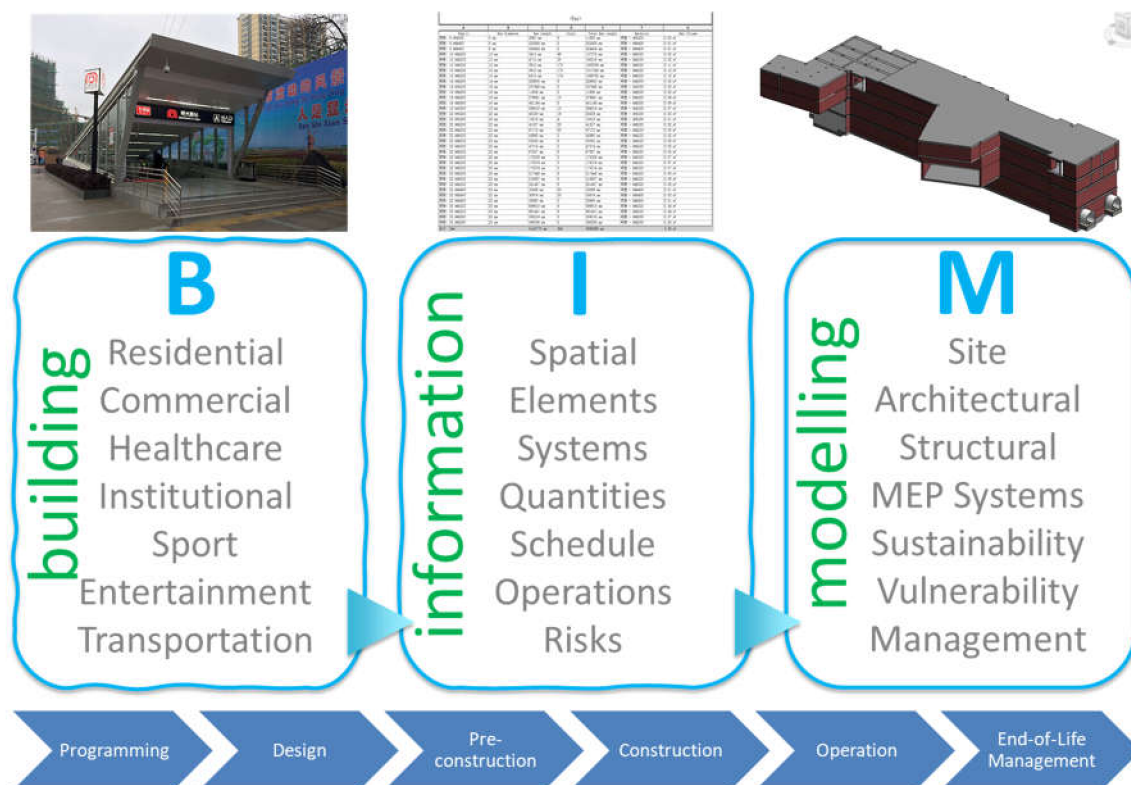
Figure 1. Digital twin concept integrated with life cycle perspective for sustainability and vulnerability audit.

2. Literature Review

The potential of digital twin (DT) or so-called building information modeling (BIM) cannot be underestimated in design, construction and maintenance management of a construction projection. At present, DT has been widely used for enhancing the design and management of projects. Moreover, it emphasizes the role of all stakeholders in a project's integrity, and distinguishes any potential issues of design, construction and operations in a simulated environment, thus promoting the development of the AEC industry [6,7]. In the same year, Kymmell demonstrated the relationship between the building information model and all required information and project planning, design, construction or operation [8]. In 2009, Hardin pointed out that the BIM technique is not only used by 3D intelligent modeling software, but also has a big impact on workflow and project delivery [9]. In recent years, many research scholars have devoted themselves to unleashing the advantages of BIM and demonstrating the benefits of BIM development to the future development of the construction industry. In Finland, the VTT Technical Research Centre focuses on exploring 4D BIM to develop procedures and use BIM technology for safety planning, management, and communications, as part of the 4D-construction planning [9]. In 2011, Salman Azhar illustrated the benefits of BIM in relation to cost and time saved by developing and using the model during project planning, design, pre-construction, and construction stages through four case studies whose data were obtained from Holder Construction Company, a medium-sized contractor based in Atlanta, Georgia [7].

With the application of BIM in the design, construction, and management of buildings and 4D simulation, BIM-based digital models also bring benefits to the safety and risk management of buildings. In 2015, Zhang et al. [10] identified and took corresponding preventive measures to reduce the potential hazards at the early stage of the construction project by developing a BIM automatic safety inspection algorithm. Despite a large number of 3D BIM applications, the use of digital twin in the railway industry is not extensive (in comparison with building sector). The industry focus is mainly on the requirement of the level of details (LOD) required for each stakeholder. BIM adoption is mainly used for program data sharing and collaboration using a data visualization technique. In fact, the extension of 3D BIM to higher order dimensions (e.g., 4D to 6D) is even relatively fewer. In this study, we further explore the advanced applications and research methods to enhance the existing 3D BIM models of the subway station project. The goal is to determine new insight into the life cycle management of subway stations or metro stations, considering carbon footprint and project costs. In addition, we aim to demonstrate the use of the digital twin for vulnerability assessment by considering various options to improve structural integrity of the subway station when exposed to extreme events.

2.1. BIM Technique and Life Cycle

In 2012, Hanneke et al. focused on the BIM technology applications in life cycle construction projects. The benefits for a project, that was using BIM technology, can be summarized as follows: BIM can enhance efficiency of work; errors and risks during construction can be identified and reduced, while providing more accurate and timely information, therefore providing stakeholders with a more intuitive understanding of the project process. However, this research was based primarily on interviews, which restrict the objectivity of the study and the relevant issues of BIM practical uses [11]. In 2014, Maezouk and Abdelaty studied the internal thermal conditions of the subway through BIM and wireless sensor networks (WSN). A BIM-based model was developed partially to read the air humidity and temperature in the subway space. The research adopted WSN sensors to measure air humidity and temperature in different areas of the subway, and to monitor the thermal comfort inside the subway to maintain passenger health and comfort [12]. In the same year, Chen and Luo discussed the application of BIM in project management, and proposed to combine BIM with the existing product, organization and process (POP) quality model to promote the development of construction management. The development of 4D BIM and its advantages was divided into three aspects. Firstly, information is unified and easy to manage; the second being that it can effectively avoid errors by integrating construction specifications into the model; thirdly, the application of 4D model ensures the whole process virtualization and timeliness of inspection, helping project participants to understand the project process more intuitively [13].

Later in 2017, Eleftheriadis et al. reviewed the life cycle assessment theory (LCA) and BIM capabilities in their papers and presented important discussions in the field of engineering and sustainable development. The researchers believed that the future building structure can be more sustainable. BIM collaboration is thus needed in innovation to improve engineering performance indicators. The researchers pointed out that the current challenges of implementing sustainability include lower project costs, customer awareness of potential benefits, stakeholder understanding of design options, and the negative impact of sustainable solutions on project structure [14]. On this ground, we propose in this study to build a BIM integrated analysis and decision-making process that focuses on the interactions between individual material elements and structures to generate low energy consumption, low carbon emissions, and sustainable buildings. In 2018, Liu and Sun demonstrated the innovative study on the life cycle based on BIM in the rail transit of Shenzhen metro line 9 [15]. However, the analysis was focused only on the cost. This study has further extended to consider carbon footprint and energy consumption in the circular economy. In addition, we aim to demonstrate new insights into the use of digital twin for vulnerability assessment.

2.2. BIM's Applied in Building Project

In 2016, Peng published a paper on BIM combined with the Ecotect model, which was made by Autodesk Ecotect Analysis for conducting a comprehensive preliminary analysis of building energy performance to evaluate the life cycle of greenhouse footprint of buildings. Based on the Nanjing Development Zone building, Peng conducted a sensitivity analysis through parameter changes to determine the parameters that have the greatest impact on building performance [16]. BIM and Ecotect models can simplify the construction process by calculating the information of building LCA. The work highlighted the estimation of carbon emissions in the life cycle of the material, and the calculation of carbon emissions of the buildings' life cycle at different stages, the ratio of carbon emissions to total carbon emissions in the three phases of the construction phase, the operational phase and the demolition phase, which could see that the carbon emissions during the operation phase are the highest. Recently, Kaewunruen and Xu [17] demonstrated the use of a digital twin or BIM and the Revit model for the sustainability assessment of King's Cross railway station in London. The 6D BIM model was studied by combining the 3D model with architectural information, construction process, and lifecycle assessment. The options of the retrofit program were to take preventive measures against the fire and terrorist attacks at the station and to select the most reasonable one. The research project can be used to provide reasonable guidance for the study of existing construction projects using the BIM models [18–21].

In summary, the application of BIM plays an important role in the architecture, engineering, and construction industry, and plays a crucial role in the study of the life cycle of a project. The application of BIM has broad application prospects for realizing the life cycle management of buildings, improving the level of planning, design, construction, and operation of the construction industry, and promoting the development of information and modernization of the construction industry. Based on previous research studies, this paper will further explore the specific application methods of BIM in the construction and maintenance management of subway or metro stations. It will highlight the analysis of the life cycle of metro stations through the model construction of the Hefei Dadongmen subway station. This study will further enhance the sustainable development of subway stations by determining the cost and carbon footprint throughout the life cycle.

3. Methodology

This section describes the key methods used within this study. In order to apply BIM technology to the subway station construction building, we have conducted a modeling simulation of the Dadongmen subway station using technical drawings kindly provided by Hefei Metro. As Yang et al. said, BIM can be involved in the entire life cycle of a building and can have an improved effect on the information exchange of the building [22]. Therefore, in addition to the traditional procedures for modeling a building, this study will also discuss building construction management improvements. This section can be divided into five parts: (1) background introduction, (2) the main goal and scope, (3) understanding BIM technology and BIM tools, (4) BIM-based project data extraction, processing, and (5) model renovation. The first part will briefly introduce the location and size of the project, whereas the second part will identify the overall purpose of BIM and BIM-related models in subway station construction projects. The third part is related to data collection, using Revit software to carry out 3D modeling of Dadongmen subway station, and by adding information such as construction process, material, and cost. The 5D models will be created for analyses to show the metro station's whole life cycle. In addition, a 6D model will be established by simulating carbon emissions throughout the life cycle of the metro station building. Finally, the transformation simulation of the 3D model will be carried out in order to show problems that the subway station may encounter and determine the most suitable transformation plan when exposed to extreme events.

3.1. Background Information of the Subway Station

Dadongmen Station is located on Line 1 of the Hefei Metro. This subway station is located at the intersection of Changjiang East Road and Shengli Road with borders near Nanlu River. The main construction area of Dadongmen Station is 34,837 m^2, with the main building area of the station of 28,274 m^2 and the auxiliary building area comprising of 6563 m^2, and the design life of the subway station building is 50 years.

3.2. Goal and Scope

This study's goal is to highlight the LCA using digital twin technology. The determination of the cost and carbon emissions of the Dadongmen subway station is also carried out. A simulation model has been established for use in the BIM-based LCA to extract specific data related to the each stage of life cycle of the Dadongmen subway station project from the digital twin model. By using the digital twin, the options for structural modifications to improve infrastructure resilience can be assessed in a similar manner. Noting that the use of integrated and semi-automated methods to acquire and process the data required by the LCA can help designers and builders manage the selection of construction materials and the management of construction plans [21–23].

The scope of this study includes cost and carbon emissions in LCA, and the cost will be divided into four phases: the project start phase (including the project investment tender phase), the project construction phase, the construction operation and maintenance phase, and the project demolition phase. By mapping with the project life cycle, the study into carbon emissions is also divided into the following four stages: (1) material preparation stage, (2) construction stage, (3) operation and maintenance stage, and (4) demolition and recovery stage.

3.3. BIM and BIM Tools

Currently, BIM has been seen as a good platform in the construction industry to facilitate building industry collaboration activities. Therefore, more and more construction companies have valued the importance of using BIM in projects to meet the needs of customers [24]. Antón and Díaz [25] claimed that BIM can help construction engineers to achieve better performance and quality by improving the information exchange of the project. BIM improves information transparency and demonstrates the benefits of facilitating collaborative work among stakeholders in the early construction of a project, which is important for reducing waste and avoiding errors in the future during the course of the project. The information of a building project contained in the BIM model can be varied such as geographic information, the quantity and attributes of the building component product materials, surveying marks, electrical drawings, pipeline information, and so on, in order to allow stakeholders to follow the construction processes and building information of the structure through BIM software to achieve the purpose of information exchange [26].

In the traditional 2D CAD work model, the communication of information may not be very clear among the stakeholders in any project stage, which can easily lead to slow project progress and result in unnecessary errors in the construction, operation, and maintenance process [27]. Construction information of BIM-based construction projects can be shared transparently at all stages, in order to facilitate the construction management personnel to find and solve problems and reduce emerging risks. Revit software is one of the most commonly used software for BIM applications. It can create 3D models directly in the software or can import 2D CAD graphic drawings to generate 3D models for easy operation and use. Sun believed that the role of information storage box management is to effectively apply information in the process of project construction management [28]. Therefore, the core of the BIM-based information management framework is the effective integration of information between different stages and among participants through BIM.

3.4. BIM-Based Life Cycle Analysis

Popov el at. confirmed that close cooperation and exchange of information in project participants can be achieved through the concept of modeling [29]. The 5D model of a project can be formed by the 3D project model, time related data, and cost related data. The 5D BIM model is mainly used for project cost estimates. A previous study supported that 5D BIM applied in the construction stage will greatly improve construction management efficiency and reduce unnecessary waste in the construction process [30]. In this study, we have converted the CAD 2D drawings of the Dadongmen subway station into Revit software and converted them into 3D models. The steel reinforcement has been modeled as an addition in the 3D models. In addition, the required information of expected costs and operational maintenance and activities is obtained from Hefei Metro to enhance the 3D BIM onto 6D BIM model for life cycle cost and carbon emission calculations. The BIM model of Dadongmen subway station is illustrated in Figure 2 and related material data in the Revit model (integrated with NavisWorks) is shown in Figure 3. This bill of materials is essential for LCA and it can be updated (if needed) to precisely identify the effects of disruptions on LCA such as COVID-19, natural hazards, multi-hazards. This versatile feature is available in BIM but may not be available for other traditional LCA software where intermitted modification is not possible.
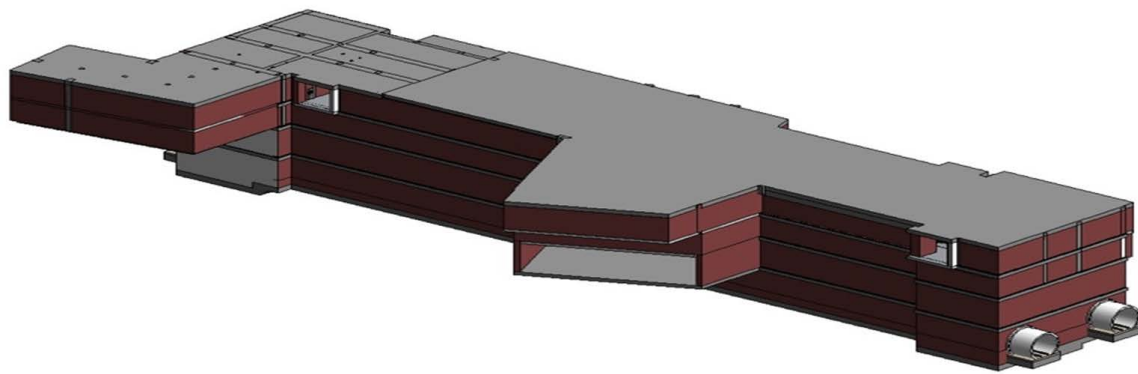
Figure 2. The BIM model of the Dadongmen subway station.

Since the concept of sustainable development is pronounced in the contemporary AEC industry, the carbon footprint of buildings and infrastructures is increasingly valued by designers, builders, and managers. Kaewunruen et al. [31] noted that the current construction industry must think over environmental impacts, such as air pollution, to underpin the sustainable development of infrastructure. Jun et al. [32] believed that users can immediately calculate the carbon emissions of construction materials based on BIM-based standardized data during the design phase when the construction options are changed or modified. In addition, in order to promote the sustainable development of buildings, researchers also put forward a BIM-based assessment method of building carbon dioxide, which objectively analyzes the consumption of any building's life cycle embedded energy and carbon dioxide emission [32]. The life cycle cost can be calculated using the net present value (NPV) principle as shown in Equation (1). The annual cashflow (*F*) at year *n* was obtained from various expected costs and expenses obtained from Hefei Metro. The interest rate of 6% was used as a benchmark in this study:

$$NPV = \sum \frac{F_n}{(1+i)^n} \tag{1}$$

This study streamlines the impact of buildings on the environment into four stages: production, construction, operation and maintenance, and demolition. According to the 2006 national greenhouse

gas inventory report of the United Nations intergovernmental panel on climate change (IPCC), greenhouse gas emissions from energy activities can be calculated using the following formula [33]:

$$C = \sum_{i,j,k} AD_{i,j,k} \times EF_{i,j,k} \tag{2}$$

where C shows the amount of carbon emission, in t. AD is the quality of energy consumed in each phase of the activity, EF is the carbon emission factor, i is the construction phase of the project, j is the equipment and materials used in this phase, and k is the type of fuel used in this phase. Table 1 is the relevant material carbon emission coefficient extracted [34].

	A	B	C	D	E	F	G
	Family	Bar diameter (mm)	Bar length (mm)	Count	Total bar length (mm)	Material	Bar volume (m³)
	01: 8 HRB300	8	1460	8	11680	01 – HRB300	0.00
	01: 8 HRB400	8	111914	2	223828	01 – HRB400	0.01
	01: 8 HRB400	8	112217	2	224434	01 – HRB400	0.01
	01: 12 HRB335	12	3415	46	157090	01 – HRB335	0.02
	01: 12 HRB335	12	4715	35	165025	01 – HRB335	0.02
	01: 12 HRB335	12	5915	170	1005550	01 – HRB335	0.11
	01: 12 HRB335	12	5915	172	1017380	01 – HRB335	0.12
	01: 12 HRB335	12	6315	174	1098810	01 – HRB335	0.12
	01: 14 HRB500	14	28326	8	226605	01 – HRB500	0.03
	01: 16 HRB300	16	29706	8	237649	01 – HRB300	0.05
	01: 16 HRB500	16	5953	2	11906	01 – HRB500	0.00
	01: 16 HRB500	16	27966	10	279661	01 – HRB500	0.06
	01: 16 HRB500	16	56396	8	451164	01 – HRB500	0.09
	01: 18 HRB300	18	29452	10	294516	01 – HRB300	0.07
	01: 22 HRB300	22	2534	16	40539	01 – HRB300	0.02
	01: 22 HRB300	22	3955	4	15818	01 – HRB300	0.01
	01: 22 HRB335	22	1654	25	41357	01 – HRB335	0.02
	01: 22 HRB335	22	3359	20	67172	01 – HRB335	0.03
	01: 22 HRB335	22	8792	5	43960	01 – HRB335	0.02
	01: 22 HRB335	22	9167	6	55000	01 – HRB335	0.02
	01: 22 HRB335	22	9475	5	47374	01 – HRB335	0.02
	01: 22 HRB335	22	11305	6	67827	01 – HRB335	0.03
	01: 22 HRB335	22	34412	5	172058	01 – HRB335	0.07
	01: 22 HRB335	22	34715	5	173574	01 – HRB335	0.07
	01: 22 HRB335	22	35075	5	175374	01 – HRB335	0.07
	01: 22 HRB335	22	36241	6	217448	01 – HRB335	0.08
	01: 22 HRB335	22	36545	6	219267	01 – HRB335	0.08
	01: 22 HRB335	22	36905	6	221427	01 – HRB335	0.08
	01: 22 HRB400	22	1654	20	33086	01 – HRB400	0.01
	01: 22 HRB400	22	2534	20	50674	01 – HRB400	0.02
	01: 22 HRB400	22	4134	5	20668	01 – HRB400	0.01
	01: 25 HRB335	25	114935	6	689610	01 – HRB335	0.34
	01: 25 HRB335	25	115239	6	691431	01 – HRB335	0.34
	01: 25 HRB500	25	111864	5	559319	01 – HRB500	0.27
	01: 25 HRB500	25	112167	5	560836	01 – HRB500	0.28
	01: sum		1156320.618	842	9569117 mm		2.58

Figure 3. Material data in the Revit model (integrated with NavisWorks). This example data is quantified from the subway station model for Family Group 01: Steel Bar.

Table 1. Carbon emission factors of main materials.

Material	Carbon Emission Factor EC (kgCO_2e/kg)
Concrete	0.11
Steel bar	2.77
Cement	0.95
Aluminum alloy	9.16
Brick	0.24

3.4.1. Material Production Stage

To collect and count building materials, data layers using Autodesk Revit software can be set up. Carbon emission factors of major building materials were determined and cross-referenced with the open literature and are listed in the reference [35]. Revit together with Navisworks enables bills of quantities and schedules. The data layer can be tailored and appended to Navisworks to generate the estimation of cost and carbon footprint. By using a conventional method of accounting, the cost and carbon counting in each stage of the life cycle can be determined (using Equations (1) and (2), respectively). If any modification of cost or material items is conducted (e.g., to improve resilience due to multi hazard risks), the cost and carbon calculations can be automatically updated.

3.4.2. Material Transportation Stage

The carbon emission in this period is mainly calculated from the use of construction materials, transportation vehicles, and field construction machinery. The materials chosen for the building are usually used and transported in proximity. Most of the building materials factories in Hefei are located in the suburbs of Feidong and Feixi regions. Therefore, we estimate that the transportation distance of materials in this project is within 10 km, to facilitate the calculation [35–37].

3.4.3. Operation and Maintenance Period

The assessment in this stage is determined from the activities arising during the operation and maintenance stage. Among them, the carbon emission of the operation stage mainly comes from the use of air conditioning, electric power of the escalator and lighting equipment. Maintenance activities and expected costs were adopted from the scheduled maintenance plan by Hefei Metro. Main maintenance activities include the facility maintenance, change of platform floors, refurbishment of station components, and some expected contingency work for appliance maintenance. The costs of the expected maintenance items during operations were obtained from Hefei Metro. Therefore, the carbon emission in the maintenance phase can be generated mainly in the process of material replacement, component maintenance, and refurbishment, which has little impact compared with the other stage of the life cycle, as reported in [35].

3.4.4. Demolition Phase

The carbon emissions present in the demolition phase mainly include the energy consumption of various construction machinery and construction waste vehicles.

3.5. Revit Model Renovation to Reduce Vulnerability

At present, BIM-related work focuses on the pre-construction research and reconstruction work of a project, but the design and management related to the sustainable development have not yet been fully studied [29]. However, Di Mascio and Wang [38] believed that digital tools have shown advantages of effective management and improvement in the edesign, organization, and construction period of renovation projects. Sibanda and Kaewunruen [39] pointed out that critical public facilities like the railway stations will encounter many dangers such as flood and fire over time, which will affect its normal service life. Due to the lack of management and retrofit plans for specific disasters, there have been many accidents in public transport facilities in history. For example, according to Global News, on 10 August 2019, Shanghai XuJiahui subway station was hit by typhoon Lekima, which caused the ceiling of the subway station to leak in water [40]. In May 2016, a flood occurred in Guangzhou, Guangdong province, China, which flooded several subway stations in the flood-hit areas. The disaster caused the destruction of equipment at subway stations and serious damage to the walls [41–49]. In this case, waterproofing of subway stations and prevention of terrorism are essential. This study is thus aimed to demonstrate the use of digital twin to help reduce vulnerability of the metro station. The renovation measures and options can be directly modified and renovated in the existing Revit

model. In flood accidents, the main reason for damage is that the material selection during construction does not have strong waterproof performance. In order to improve the waterproof performance of subway stations, this study has adopted mainly three renovation options: (1) application of carbon fiber reinforced polymer on columns (CFRP), (2) the use of removable modified steel jacketing (MSJ), and (3) the use of ductile concrete (DUCON). The detailed breakdown of structural modification options, materials used, and relevant costs was previously studied in [39,50–52]. Cost estimates and carbon emissions for each scenario can then be determined and compared. Technical discussions related to the retrofit modeling will be conducted to identify and rank potential solutions to emerging risks.

4. Results and Discussion

Based on the aforementioned LCA method and real case studies, this study embarks on the calculation of life cycle costs and carbon emission of the Dadongmen subway station using a digital twin. Targeted innovative assessments are carried out on the project through the Revit model together with Navisworks. The tailored spreadsheet layers were developed in Navisworks to calculate cost and carbon footprint from the bills of quantities obtained from Revit model. Certain cost information was obtained from Hefei Metro for various activities throughout the life cycle stages (e.g., design costs, planning cost, services costs, transportation, materials' unit costs, etc.). The accounting method was adopted in order to estimate total cost items and carbon footprint derived from all materials used (e.g., cost = material price × quantity of materials; embedded carbon = carbon emission factor × quantity of materials) [39,44,45]. After annual cashflow items are calculated, Equations (1) and (2) were adopted for LCA in each stage of life cycle. Tables 2–4 are obtained by using Navisworks to identify the quantified bills of materials from BIM model and correlate the information with developed databases derived earlier and from [44,45]. In this section, comparable LCA results are highlighted.

Table 2. The cost estimation results of the Dadongmen subway station.

Stages	Costs (Millions Yuan)
Preparation	0.65
Construction	25.79
Operation and maintenance	1.37
Demolition	5.42
Total	33.22

Table 3. The carbon emission estimation results of the Dadongmen subway station.

Periods	Carbon Emission (t)
Material production	13,023.31
Construction	3255.80
Operation & Maintenance	37,987.84
Demolition	2279.06
Total	56,546.01

Table 4. The main material carbon emission estimation result of the subway station.

Material	Carbon Emission (t)	Proportion (%)
Concrete	5685.98	43.66
Steel bar	3871.83	29.73
Cement	785.31	6.03
Aluminum alloy	2297.31	17.64
Brick	337.30	2.59
Others	45.49	0.35
Total	13,023.31	100

4.1. Life Cycle Analysis

According to Table 2, Figure 4 can be established to illustrate the life cycle cost of the subway station. It can be found clearly that, by considering the life cycle cost of the Dadongmen subway station, the cost of the construction stage reaches nearly 26 million yuan, accounting for 78% of the total life cycle cost estimation, which is the most expensive stage out of the four stages throughout the whole life cycle of the subway station. Apart from the construction, the end-of-life management is the second most expensive activity required during those circular economy stages. It is clear that the planning and preparation process requires or consumes the least resources. Since most maintenance activities of the subway station are simply material or component replacements, the maintenance stage emits relatively lesser carbon and the maintenance cost is negligible. This finding also confirms that track slab systems tend to yield minimal maintenance activities and subsequent costs in comparison with ballasted track systems, similar to other works [48,49].
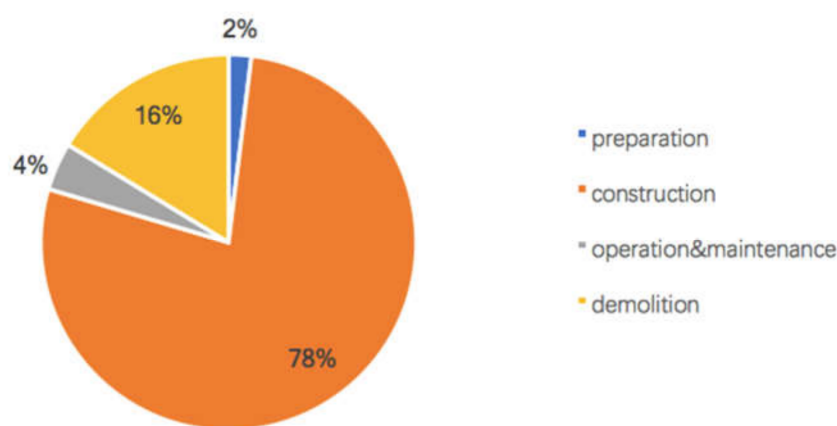
Figure 4. Project cost emission results (percentages of life cycle cost).

This study also calculates the carbon emission of the subway station based on the BIM, and the results are shown in Figure 5 and Table 3. It exhibits that the carbon emission throughout the whole life cycle of the subway station is 56.6 thousand tonnes, among which, the carbon emission in the operation and maintenance of the subway station reaches 38.0 thousand tonnes, accounting for 67% of the total carbon emissions in the whole life cycle. The reason is that the period of operation and maintenance is a long-term carbon emission phase with the lengthiest time and highest energy consumption during the whole life cycle. For instance, the construction phase is around 4–6 years, while the operational phase is more than 50 years. It is noted that the economic service life (operational phase) is often taken as 50 years prior to end-of-life management (although some rail networks might shift economic service life to 75–120 years when the networks are ageing). The environmental impact of the project is measured by carbon emissions from transportations and construction material productions. The main structural materials of the project are rebar, concrete, cement, concrete block, and aluminum alloy. The material productions emit about 23% in total. As show in Table 4, concrete accounts for 44% of total carbon emissions from material productions, while steel and aluminum contribute 30% and 18% to greenhouse gas emissions, respectively.

The end of life management considered in this study is the demolition for renewal and replacement. It should be noted that some other methods can be considered depending on the residual conditions such as refurbishment, structural upgrade and modification, and/or structural retrofitting. By considering Figure 5, it is clear that to minimize whole-life greenhouse gas emission, the material selection and the maintenance activities should be streamlined too. Rethinking material usage and track system design, which are the key contributors, can enable long-lasting service life and minimize annual maintenance activities.
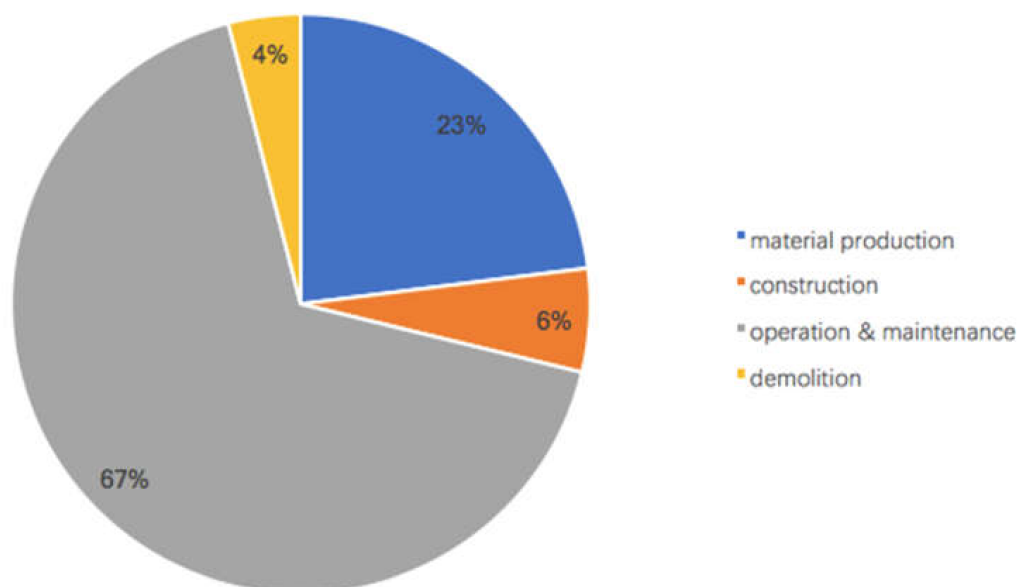
Figure 5. The project's carbon emission estimation results (percentages of life cycle greenhouse gas emissions).

4.2. Results and Discussion of Renovation Management

According to the aforementioned parameters, CFRP, MSJ, and DUCON materials have been used to retrofit the railway stations in order to prevent and alleviate the flooding disasters and terrorist attacks. These are the top critical risks for subway stations globally. Since the structural concrete is highly tolerant to extreme temperatures, the natural thermal effect is negligible for subway station infrastructures [53–55]. The detailed breakdown of information related to the cost and carbon footprint of each material used in the retrofit options can be obtained in Refs [39,50–52]. The cost estimation results are shown in Figure 6. In the cost estimation, the MSJ cost is the lowest, only 2.2 million yuan, whilst the expenses for DUCON and CFRP are relatively more expensive or about 42.9 million yuan and 37.5 million yuan, respectively. In the calculation of carbon emissions as shown in Figure 6, the carbon emission of CFRP is only 11.0 thousand tonnes, while MSJ is 11.1 thousand tonnes. In contrast, the carbon emissions of DUCON is the highest of the other two options, which is about 37.0 thousand tonnes. In this study, the resilience of critical infrastructure with respect to emerging risks and uncertainties is highlighted by calculating and evaluating the economic and environmental impacts of different project transformation schemes. Considering the economic cost, environmental impact, and life cycle of the project, the modified steel jacketing (CSJ) is considered to be the most suitable modification program to minimize the vulnerability and improve the robustness of the subway station. Note that the practicality of each method is excluded from this study, including the time consumption of setting, preparation, planning, design, and modification to install the retrofit methods.
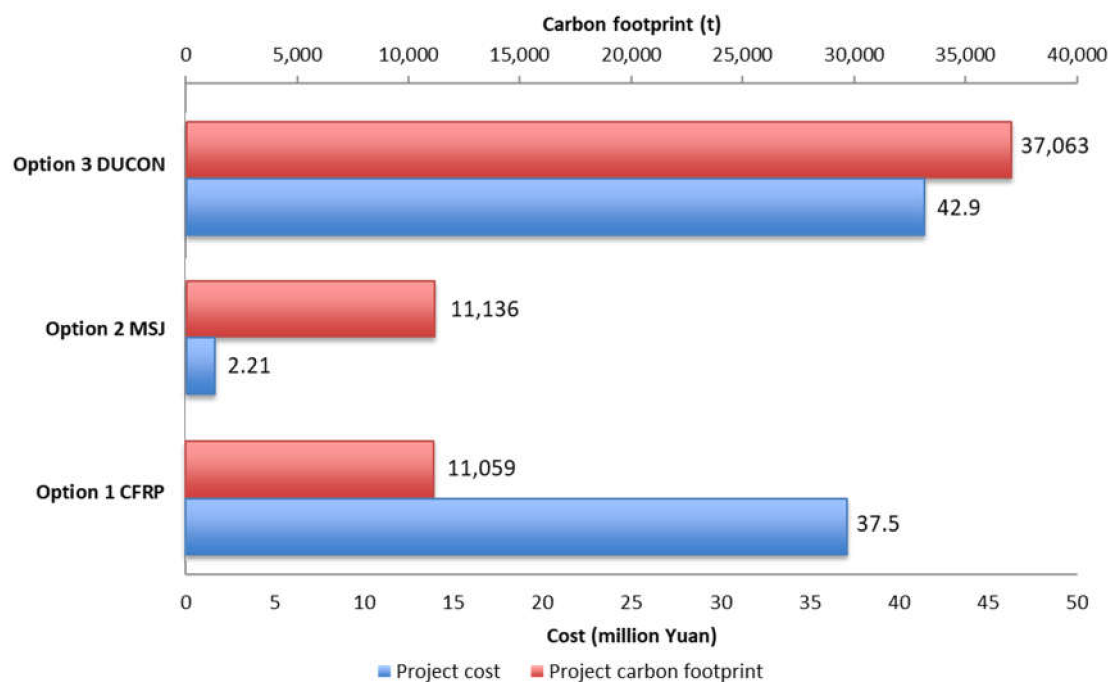
Figure 6. Comparison of the project's cost and carbon footprint estimation of three renovation options to improve resilience of railway station.

4.3. Discussion on Digital Twin Development and Limitation

As China's AEC industry increases more concern for better environments, it is predictable that LCA will be fully developed in the near future and will be further discussed and studied by researchers and practitioners in the industry. In order to carry out LCA, ones must overcome such obstacles as the lack of database, time, and mutual operation of data.

This study embarks on the modeling and analysis of the building structure of a subway station. The emphasis of this work is placed on the structural components, whilst electrical cables, pipes, and other appliances are not within the scope of this study. The complete station building was established using the digital twin to accommodate all various parts, including all platform, staff office, station foyers, corridors, and tunnels. Since the establishment of BIM models of different majors requires different BIM software, it is very complicated to assimilate all professional models and data for integrated facilities with BIM, which makes it problematic to realize data interoperability. It can be noteworthy that the development level of model accuracy, or level of details (LOD), can be regarded as a qualification to prove the reliability of the BIM model. Currently, most building models require LOD at a certain stage, so that the required LCA data information can be obtained from BIM models automatically. Solihin and Eastman [42] pointed out that LOD300 can calculate construction capital investment, makes transportation plans, and simulates energy consumption in the operation stage by obtaining the size, shape, and location information of various structures, while LOD350 relies on the use of other building systems [43]. Therefore, LOD of the BIM model should be adjusted according to the LCA to facilitate participants to accurately extract data used in building LCA from the BIM model. In this study, the data were obtained from the engineering consultant and relevant China Metro Authority (i.e., Hefei Metro). LOD300 level was established in this study. The dimensions of all components in the digital twin are identical to the technical drawings (including rebars and reinforcements). Since the data on the actual dimensions of real constructed facilities are not available, it is assumed that all components are perfectly constructed in accordance with the technical construction drawings. The potential deviations, which are the uncertainties in this LCA, could be derived from human errors during constructions, on-site modifications of components, undocumented retrofitting of the components (if any), poor construction quality, and poor use of materials. Although these

uncertainties are not within the scope of this study, it is estimated to be around 5–15%, which could result in around 2–5% of cost variation and 8–10% of variation in carbon footprint estimation of the subway station.

In this study, existing BIM has shown some limitations. Navisworks were used as an addition in order to help determine LCA. When structural modifications are applied to BIM, the calculation needs to be updated or re-calculated manually. In addition, structural tolerances (e.g., construction errors) cannot be properly appended to the model so that we could not automatically conduct an uncertainty quantification. The defect data obtained were appended as information layer, which restricts the ability to identify and visualize severities. On this ground, the vulnerability assessment requires experienced engineers to justify and further validate. Revit has recently introduced Dynamo Scripts where developers can program BIM to suit any applications. Our future work will embark on the development of a new algorithm using Dynamo Scripts that can automatically link and re-update the BIM with other critical information such as time dependent damages, which enable practitioners and engineers to detect vulnerability better. This can help engineers develop a more variety of low-cost and low-carbon solutions to emerging risks and manage uncertainties more effectively in practice, as well as improve sustainability in infrastructure resilience.

5. Conclusions

This unprecedented study illustrates the digital twin or BIM technology applied to a subway station project, and demonstrates that BIM can accurately support the LCA model and yield acceptable accuracy of LCA outcomes, especially when random updates are inevitable (e.g., due to disruptive maintenance, natural hazards, etc.). In this paper, the digital twin is established through the collection of project information, which provides a visual platform for project participants to share information, improve the efficiency of project engineering, and reduce errors and risks in the project process. In addition, through the integration of 3D models, the construction schedule, cost estimation, carbon emission calculation, and other information model data are obtained to develop the 6D model. Based on the project of the Dadongmen subway station in Hefei, the development of BIM technology to enrich LCA makes use of the relevant data obtained from Hefei Metro. This study provides a new insight into the use of digital twin for risk-based maintenance and retrofits over the whole life cycle of subway stations. It is clear that the digital twin can also be used for vulnerability assessments of the subway station by identifying potential retrofit options. The potential effects of disruptions (e.g., natural hazards, man-made hazards, etc.) on LCA can be captured, shared, and visualized for better risk communication with stakeholders. The limitations of digital twin technology in project information exchange and model layer updating were discussed. In the future, the digital twin model will be modified and re-updated automatically as the project changes, so that the project has an effective model to manage risk dynamics throughout its life cycle. The new insight obtained from this study can help engineers and practitioners develop and adopt digital twin technology for more applications in the construction process of any infrastructure project. The digital twin can optimize the construction information of the project, improve the construction efficiency, reduce the cost and carbon emission, and perhaps assess and reduce vulnerability in order to improve infrastructure resilience more sustainably.

Conflicts of Interest: The authors declare no conflict of interest.

Data Availability: All data, models, and code generated or used during the study appear in the submitted article.

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