Dynamo script and a BIM-based process for measuring embodied carbon in buildings during the design phase

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Abstract

In recent years, worldwide efforts have been made towards reducing energy use and emissions, which have a variety of impacts such as contributing to climate change. Hence, environmental analysis in the construction sector is essential today to develop good products that perform adequately, are safe, cost-effective, and environmentally friendly. A significant emission from various stages in the building sector is carbon dioxide, which can be separated into two categories: embedded emissions and operating emissions. The aim of this paper is to introduce a simple tool integrated into a building information modelling (BIM)-based framework that provides an analysis of embodied carbon (related to the SE2050 commitment to net zero) in order to produce a manual to guide designers in selecting appropriate materials, systems and alternatives during the design phase of a construction project. The suggested integration procedure was carried out using Autodesk Revit (to produce the 3D model), Dynamo (a visual programming tool), and BIM360 (to link with), with good interoperability between each product. To finish, a case study was carried out to apply and validate this process and verify that the tool is ready to use. The results show that the maximum variance was 0.047, which supports developers' environmental strategies, and enables clients and other stockholders to consider environmental impacts during the early phases of construction projects.

Keywords: sustainable buildings; building information modelling (BIM); energy consumption; energy efficiency; embodied carbon

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1 INTRODUCTION

Globally, the demands and requirements of industries and their various products are growing daily. All these products consume a lot of energy and create an abundance of different emissions [1]. These emissions have direct and indirect effects on the surrounding environment; climate change and global warming are good examples of what the world is currently facing. Many conferences have been held and scientific studies published to discuss ways to decrease emissions and improve future industries in order to minimize adverse environmental side effects. COP27 held in Egypt in 2022 was such an event; it introduced and incentivized the world to transfer to other sources of energy with low emissions, such as renewable energy. In fact, the construction industry is a

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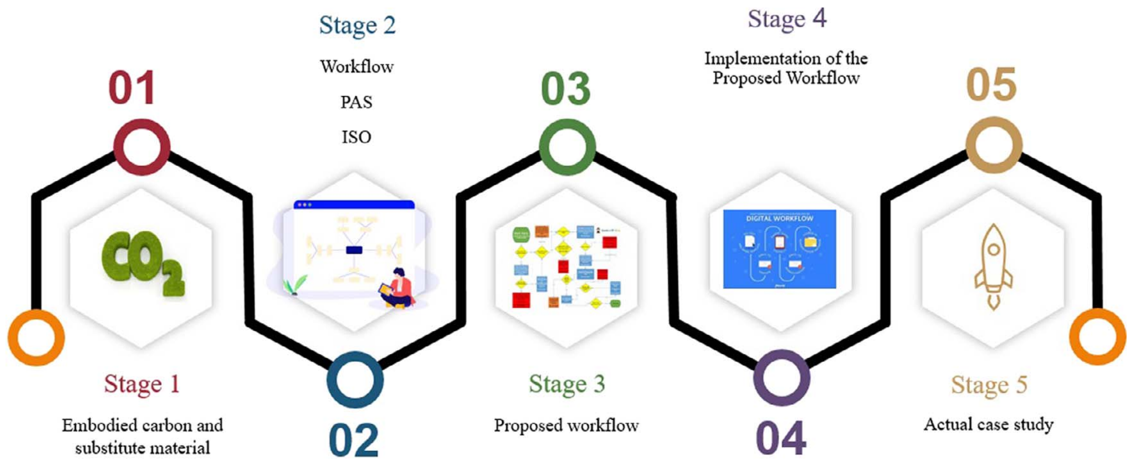


Figure 1. *Research methodology.*

major source of a variety of emissions as shown by the statistics produced by, for example, the US Department of Energy (2021). Moreover, previous studies have claimed that the raw materials of the construction industry are an important source of embodied carbon dioxide (CO_2) emissions. These emissions are emitted throughout the life cycle of a construction project from design to demolition stage according to a cradle to grave analysis. Thus many building developers and software companies have issued software and applications to encourage designers to consider the environmental impacts of their construction sites. Unfortunately, the software and applications are very expensive and some expertise is needed to use them in the construction industry. Since the introduction of building information modelling (BIM), a lot of these problems have been resolved through good integration between the modelling software and other software used in environmental analysis and calculation of CO_2 emissions. The complexity of software integration and its problems are still a big obstacle facing designers and developers, in addition to the high costs and complex workflows of multi-disciplinary projects. According to the traditional workflow proposed by PAS 1192 and the new workflow in ISO 19650, environmental analysis is placed after the design phase (Architect—Structural— . . .), which creates a big gap between them. Based on this understanding, designers are frequently forced to redesign and recalculate to achieve compatibility between their designs and environmental requirements, which is costly and time-consuming. Weytjens *et al.* (2012) [2] found that integrating environmental elements at design stage is the best way to decrease time and cost and introduce the optimum design, while satisfying both design and environmental requirements at the same time and before the execution phase. Bragança *et al.* (2014) [3] observed that the conceptual phase is the best stage to predict a building's sustainability performance. Lagios *et al.* 2010, Jakubiec-Reinhart 2011, Niemasz *et al.* 2011, Paoletti *et al.* 2011, Roudsari and Pak 2013, Shi and Yang 2013, among others have published research dealing with the integration of environmental analysis into the design phase, including embodied CO_2 optimization [4]. Their studies also introduced

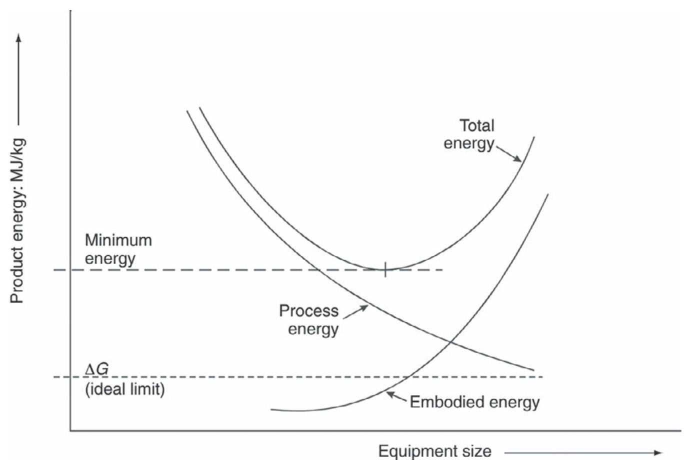


Figure 2. *Relationship between process and embodied energy [32].*

development frameworks for energy saving using the BIM tool mainly at the conceptual phase. That is to say that there are currently no studies dealing with the integration of the calculations of embodied CO_2 (related to SE2050's commitment to net zero) using the BIM model. In this paper, embodied CO_2 calculations using the BIM process will be introduced as a framework to improve the traditional framework set out in ISO 19650.

The Life-Cycle Assessment (LCA) technique, which is standardized globally, helps to quantify the environmental pressures associated with products, the environmental advantages, the trade-offs, and areas for improvement while taking into account the entire life cycle of the product. The ISO standards describe the framework of LCA [5, 6], which can include both social and economic issues [7]. But using LCA in the construction sector is still very rare [8]. Sustainability assessment frameworks, such as EN 15643 [9], have been innovated by top designers and engineers to evaluate building performance in a standardized and systematic way. LCA standards measure environmental performance based on the calculations that have been adopted by engineers [10]. The

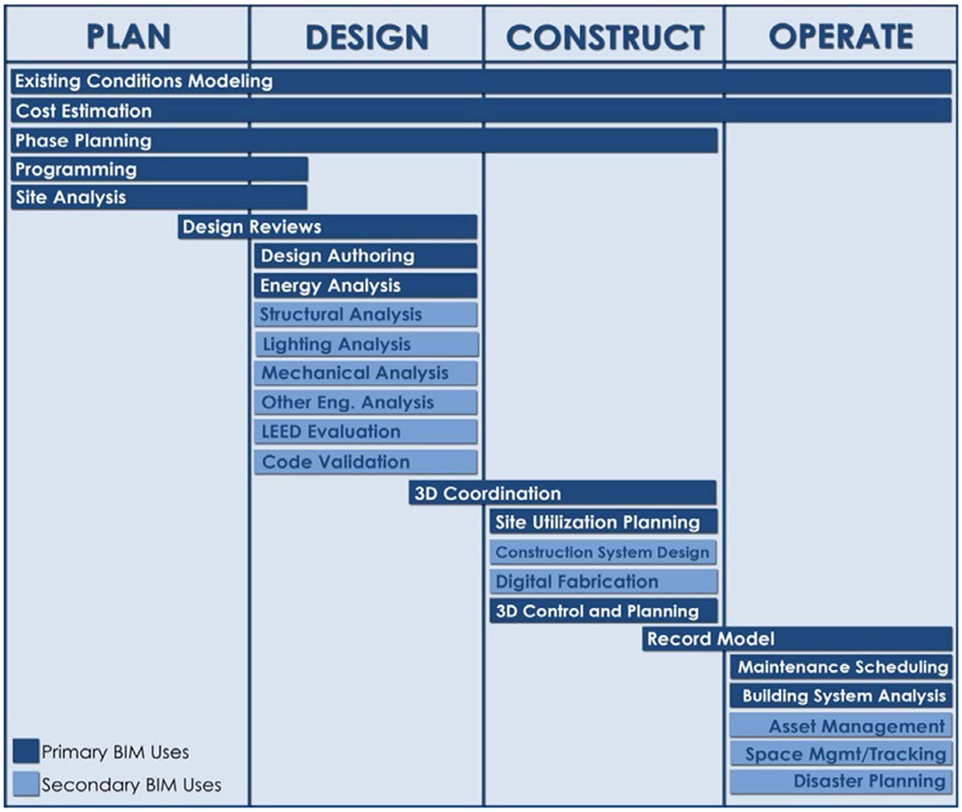


Figure 3. *BIM Uses—project life cycle [33].*

Life Cycle Costing in Construction (LCC) methodology has been designed in line with EN 16627 and ISO 15686-5 standards, which are based on the DGNB system [11, 12]. In contrast, the standard EN 16309 [13] methodology for social performance assessment is not currently used in practice [14]. Not many studies have used S-LCA (Social Life Cycle Assessment) in an attempt to build products [15, 16]. Most studies shows the difference between the level of maturity of all three methods (S-LCA, LCC, LCA). Soust-Verdaguer *et al.* and Bueno *et al.* provide a review of the latest developments [17, 18]. LCA including 28 commercial tools have been provided recently by Cavaliere in [19], seven of which used a BIM model. Moreover, many scientists and researchers have developed their own ways to connect the BIM database with an LCA in a new workflow using Revit, ArchiCAD with SimaPro, or Excel [20–22].

BIM has the advantage of decreasing the need for additional LCA by using digital tools and thus speeding up the process. A lot of scientific studies about BIM-based LCA have been published over the past decade and have assisted scientists in developing new software tools.

In many recent studies, the most frequently used visual programming plug-in to connect the LCA database and the BIM model is Dynamo for Autodesk Revit. Although most existing studies present methods for conducting BIM-based LCA at the design stage, usually employing a high level of development (LOD)—LOD 300 or higher—during later design stages [23].

To date, no study in the literature has applied these tools to the whole process. To provide feedback for designers and engineers and inform decision-makers the LCA results need to be available early in all stages, especially at the design stage [24]. Cavaliere *et al.* offer a general concept to apply this method throughout the different planning stages using BIM-based LCA with high LOD [25]. But they describe only a theoretical framework with no case study or real application while Cavaliere outlines a different concept of links between several data and provides a theoretical case study for the application of the framework. Although, they investigated the BIM-based LCA through the design stages that allow a high-performance improvement or environment. The study objective is to analyse the link between quantity take-off from BIM software with LCA through the database and the tools of the established approach for assessing environmental impact.

Instead of using the volumetric definition of building elements of an office building in Switzerland, this approach is applied to the design process of a real case study, and it only uses the information through a 3D model with a typical simplified LCA.

All the building components and the fragment structure materials can be easily assigned from a library. By using a building performance simulation (BPS) this approach uses thermal models that consist of 2D surfaces only, which are called 'shoe-box' models [26].

[26] for example. Material variants can easily be evaluated as the model does not need to be changed, just a new component

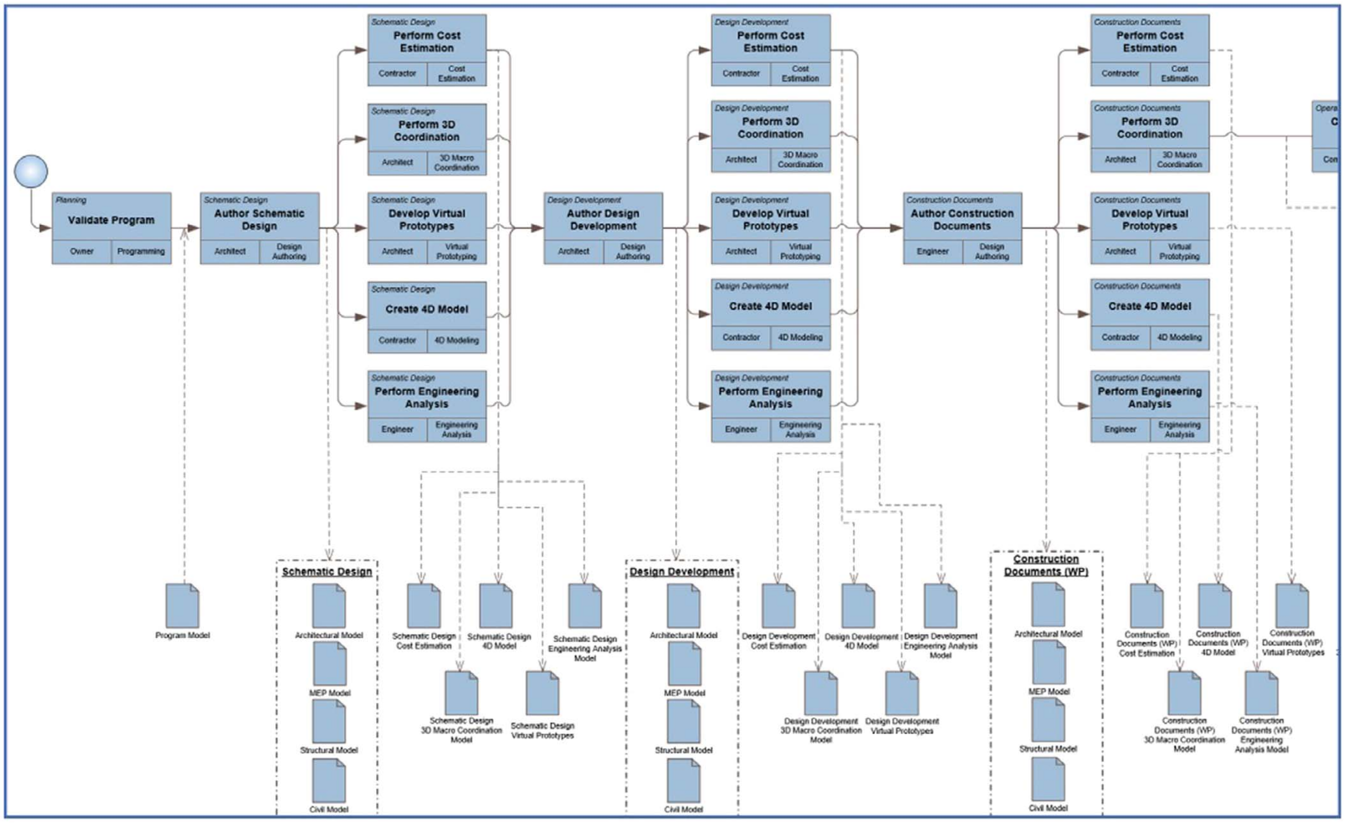


Figure 4. *Detailed process map [33].*

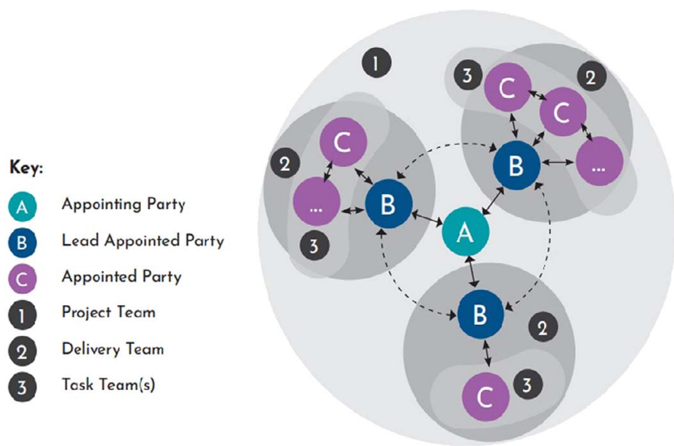


Figure 5. *Interface between the parties and teams in terms of information management [5].*

selected from a catalogue. The decisions and clashes between designers could be caught early in design changes. The context of BPS studies the extractions of three dimensional models from volumetric BIM models through the various stages. Farzanek *et al.* and Gao *et al.* describe a recent study on gbXML (Green Building XML) as a common format for these models, which could be extended to include attributes for LCA [27, 28]. Furthermore, direct BIM–BPS links using IFC have been developed [29]. But as yet there is no common way to extract information among architectural offices [29, 30]. The sustainable certification used the same tool in the early design stages. The use of 2D models has some inherent inaccuracies [31]. The user will want the model to be as accurate as possible and so may prefer to use 3D models as good and trustworthy sources of information. The selected materials from a catalogue with a specific code would be more easily and clearly.

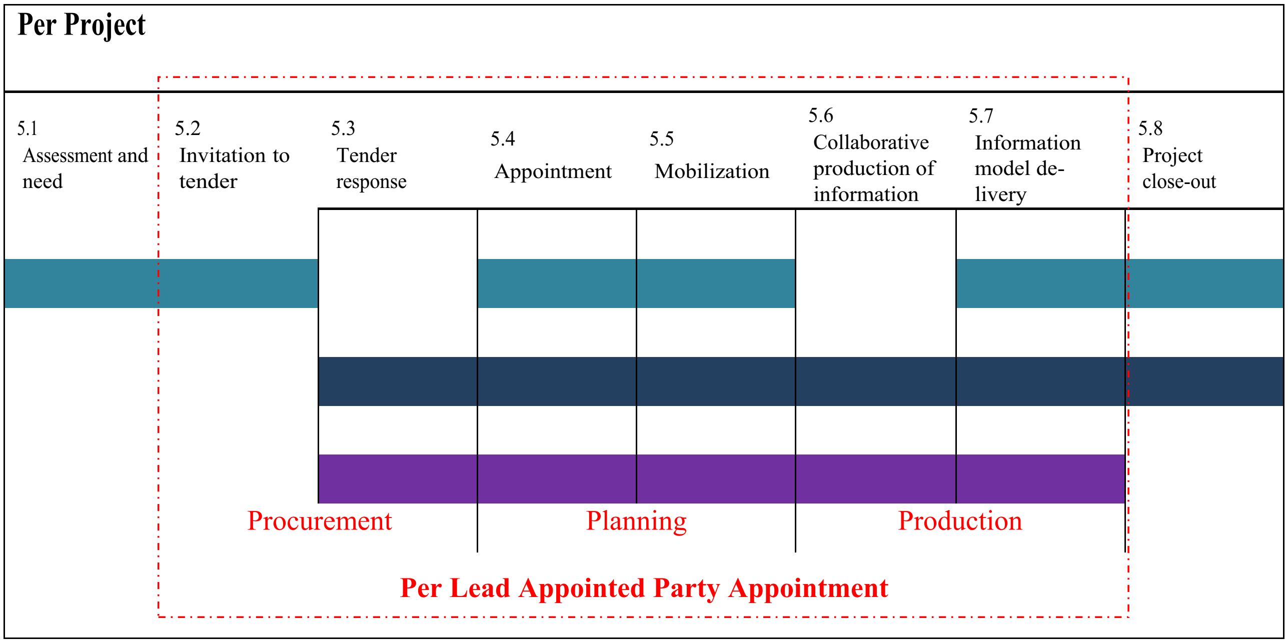
In summary, the main objective of this paper is to introduce an easy tool integrated BIM-based framework that provides an analysis of embodied carbon to produce a guide for designers to choose the suitable materials, systems and various alternatives at the design phase. The proposed integration workflow was done using the best-known BIM platforms represented in Autodesk Revit, with its visual programming tool Dynamo and its packages represented in BIM360.

2 RESEARCH METHODOLOGY

To satisfy the research objectives, there were five steps as shown in Fig. 1, which are:

1. Application of embodied carbon emissions and substitute materials in the construction industry.

Table 1. *Different activities of the various parties*



2. To present the current traditional workflow related to PAS 1192 and ISO 19650 with a discussion of the position of environmental analysis including calculations of embodied CO_2.
3. To introduce a proposed new workflow.
4. To implement the proposed workflow.
5. To describe an actual case study to demonstrate the new workflow.

3 BRIEF OF AN EMBODIED CARBON AND SUBSTITUTE MATERIALS IN THE CONSTRUCTION INDUSTRY

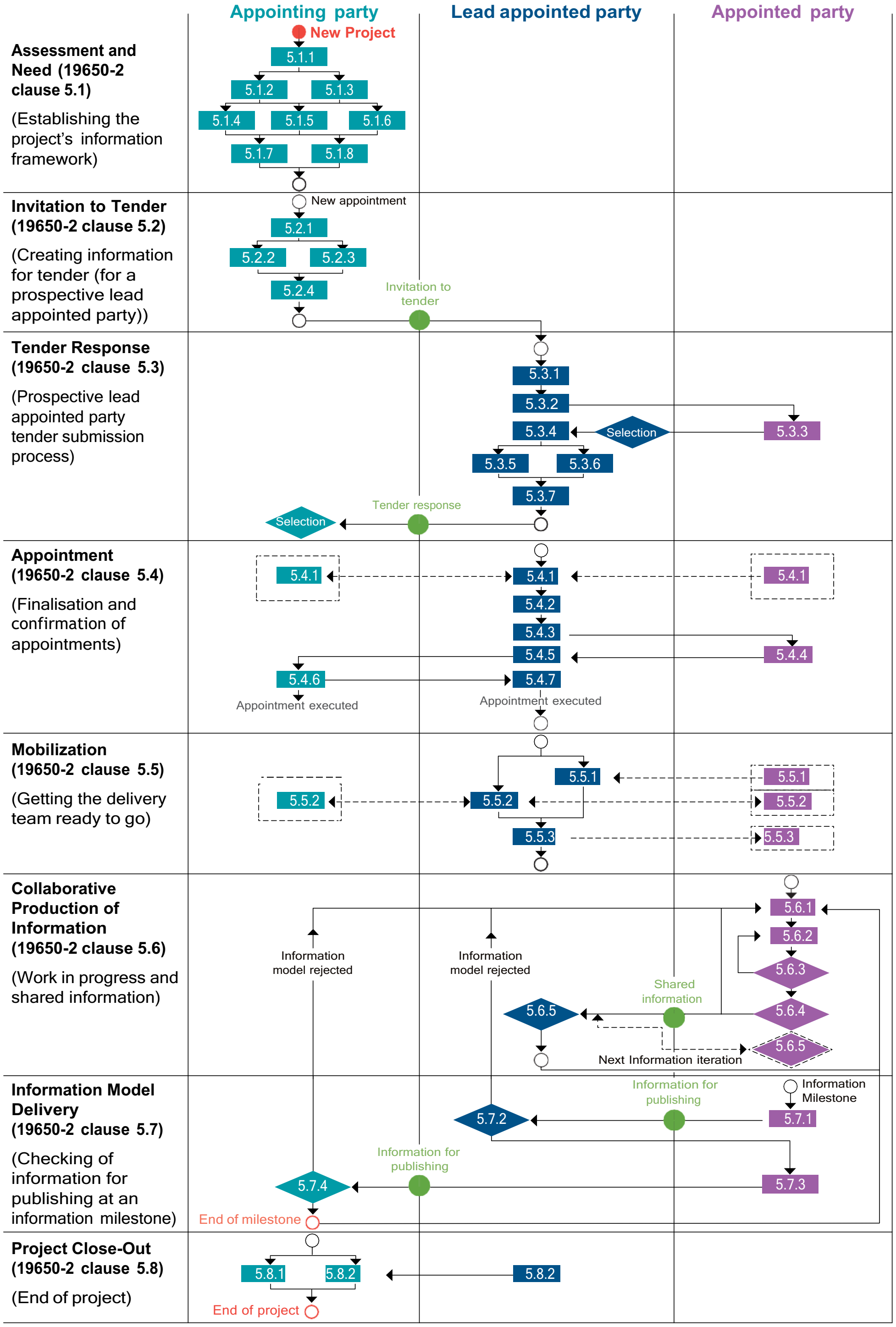
The expression 'embodied energy' appeared at the end of 1970, and peaked in 1973/74 and 1979/81 after the oil crises. There are many definitions of embodied energy [32]. Hammond and Jones defined embodied energy as the quantity of energy required to process, and supply to the construction site, the material under consideration [32]. Summing the energy inputs over the major part of the material supply chain or life cycle is the most common method to measure and account for these embodied energies. This method can also be expressed as input/output table analysis with process analysis. Rawlinson *et al.* discussed a 'cradle-to-site' approach, including raw material extraction, processing and transportation to the construction site [33]. A study introduced by Van Gool illustrates the trade-off relationship between process and embodied energy as shown in Fig. 2.

Producing construction materials consumes a lot of energy, so sustainable materials and alternative construction materials have been produced on the construction market as substitutions for the current material, mainly cement and reinforcement steel. Pulverized fuel ash (PFA) or fly ash, silica fume, limestone fines and ground granulated blast-furnace slag are the most common and well-known alternatives to cement, which depend on the concept of 'pozzolans' providing silica that reacts with hydrated lime. Also, carbon steels, alloy steels and stainless steels are the best-known alternatives to traditional steel reinforcement. All of these alternatives and others are produced to minimize the consumption of energy and decrease all types of emissions but mainly CO_2. Due to the importance of this topic, many organizations and governments have issued specifications to organize the construction industry to take environmental impacts into account. The UK has created a database of embodied energy and carbon for construction materials on the construction industry market. These issues are funded and supported by the Carbon Trust and the Engineering and Physical Sciences Research Council (EPSRC) in the UK. In addition, the Structural Engineering Institute (a famous research centre that specializes in this topic) under the supervision of ASCE has published a database and user guide on calculating environmental impacts and embodied carbon, which is called the 'SE2050 commitment to net zero'.

4 CURRENT WORKFLOW AND ISO 19650 INFORMATION DELIVERY SYSTEM

The BIM Execution Planning Guide (BEP) is a comprehensive document that organizes and arranges all processes and steps between all parties and disciplines. It also determines the

Table 2. *Information management process and project delivery*



workflow and all the output documents for each party in the project. Twenty-five BIM Uses have been identified at all phases of the life cycle of the project. The job description for each user of each of these uses is also defined and explained in the BEP Guide. The implementation of BIM practices highlights a number of benefits to all members of a project team; nonetheless, current practices within the AEC industry are not formatted to facilitate integration between the distinct project phases (design, construction and facility management). Fig. 3 concludes that BIM has benefits at every stage of the facility life cycle, starting from

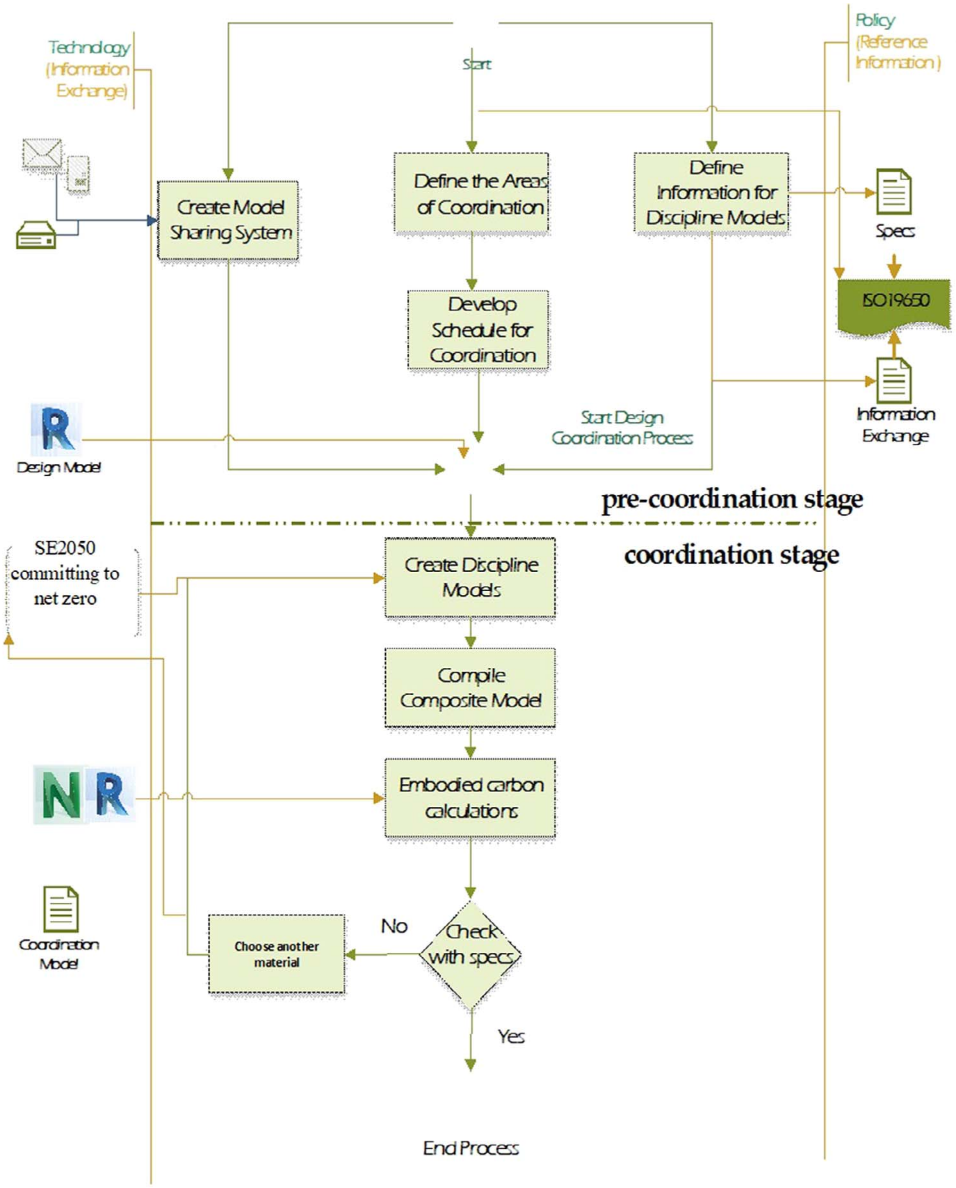


Figure 6. *Proposed workflow for coordination at design phase.*

the planning stage through to the operation and maintenance stages. These steps and guides have been issued to enhance the opportunities for the success of the project and to minimize clashes between the disciplines, mainly during the design phase.

Detailed maps setting out the process and sequence for each discipline and the type of documents that will introduce the BIM Execution Plan are shown in Fig. 4. Then, the project head or director of each discipline can make another detailed map to manage the internal documents flow.

The ISO 19650 series refers to the Appointing party, Lead appointed party and Appointed party, and the Project team, Delivery team and Task team as shown in Fig. 5.

The associated activities are set out in ISO 19650-2 clause 5 and cover eight stages outlined in Table 1.

As shown in Table 1, clauses 5.1 and 5.8 relate to a project as a whole. Activities set out in clauses 5.2 to 5.7 are repeated for each piece of work the Appointing party (client) tenders (be it for consultants, contractors and/or specialists). Table 2 shows the process at each stage for all parties and disciplines involved in the project, and describes the process of information management at each stage in more detail.

5 DEVELOPED WORKFLOW EXPLANATION

The BIM Project Execution Planning Guide is a well-documented, systematic procedure aimed at ensuring that all project

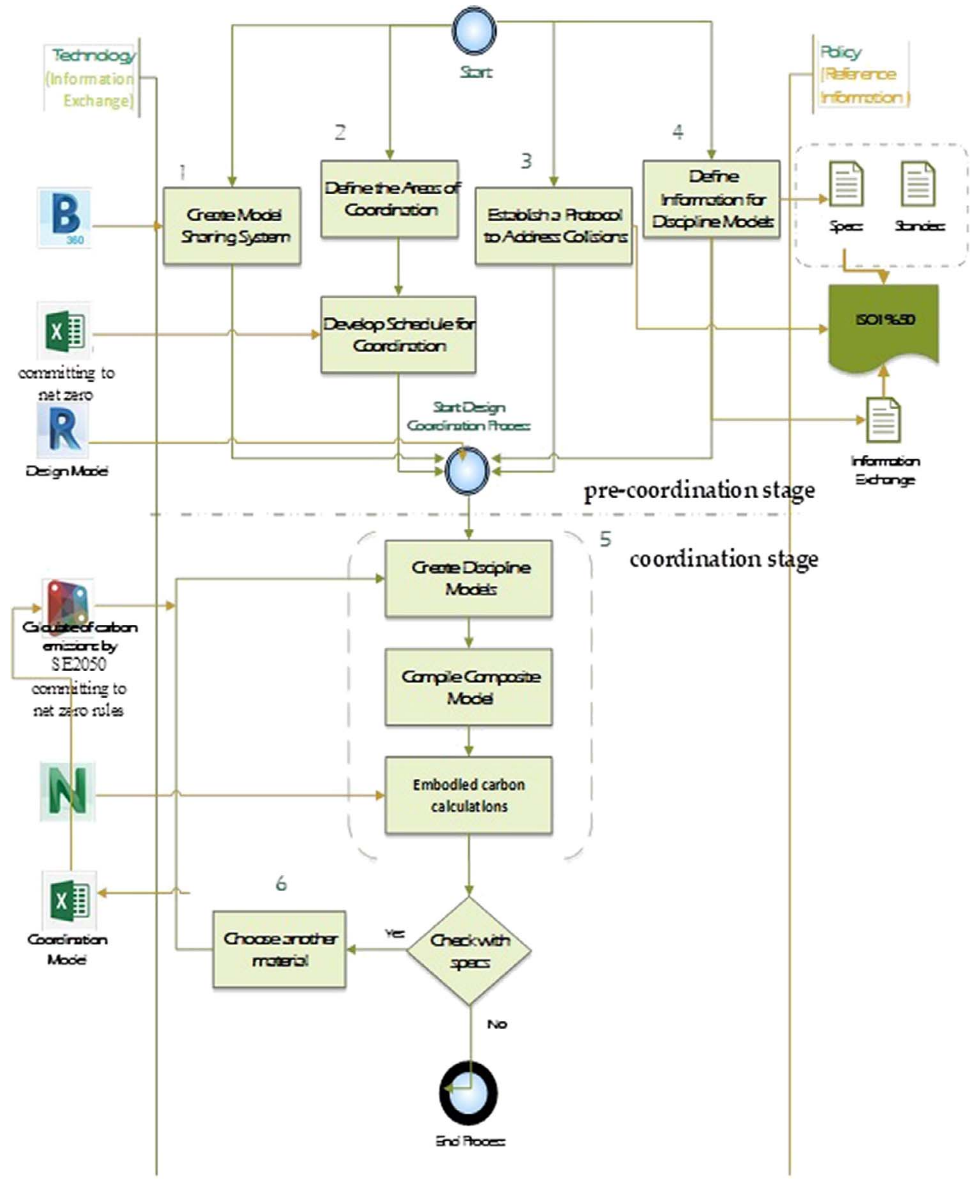


Figure 7. *Implementing the proposed workflow.*

stakeholders are fully aware of the BIM prospects associated with efficient BIM implementation. The 'design coordination' process is one of the most important of the BIM Uses. As shown in Fig. 6, a process will be constructed to highlight the sequencing and interaction between the specified BIM Uses.

This workflow illustrates the work process for each member of the design team, such as the import and export documents, type of sharing file and the interaction between the files within the defined protocols, technologies and policies. This workflow enables good coordination between the design team including on environmental impact (mainly the embodied carbon calculation) and collects all fragmentation data into one model to help the decision-maker at the design phase. The proposed workflow is divided into two parts, as follows:

- Part one: the pre-coordination stage (which includes all BIM contract addendums, specifications, standards, protocols and the collaborative work area) is a very important step that creates an integration model from different disciplines using the same type of software or by using IFC files.
- Part two: the coordination stage for the design team. This involves the embodied carbon calculations of the project to help the design team to address these at an early design stage.

6 IMPLEMENTATION OF THE PROPOSED WORKFLOW

To implement the proposed workflow requires a good combination between Dynamo (visual programming tool) and BIM360

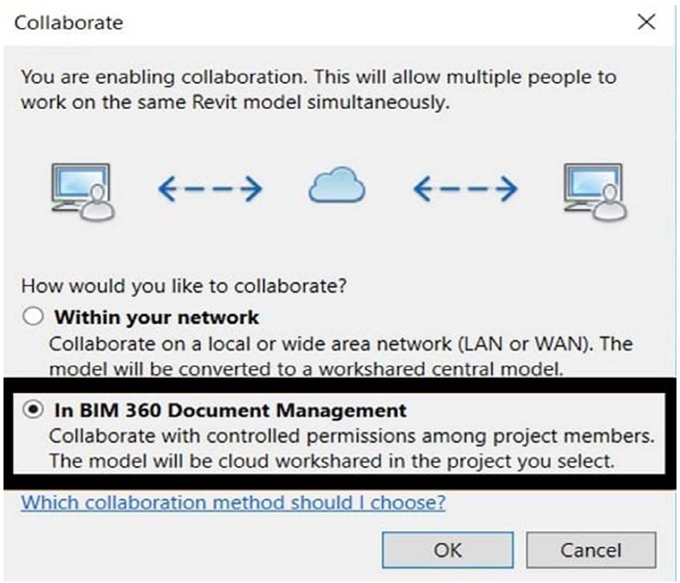


Figure 8. *Creating a model for a sharing system (generated using Revit).*

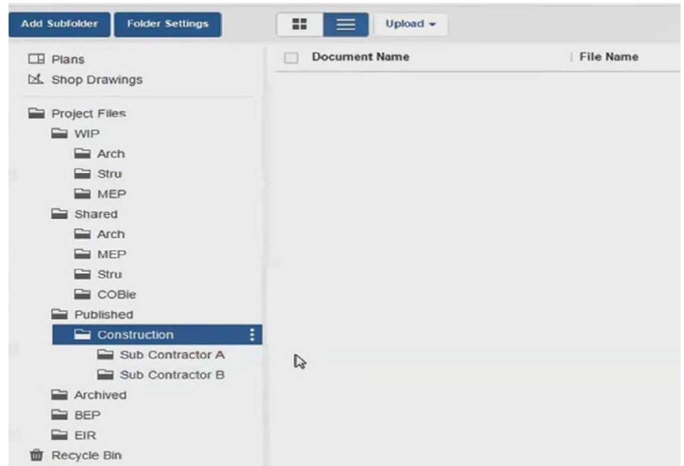


Figure 9. *Folders for a sharing system (generated using BIM360).*

(storing and managing data at BIM) with walkthrough 3D plug-in, which is a BIM enabled-tool for 3D visualization, used for detecting project coordination through visualization. The integration of all these tools with the Revit model helps the project designers to correct their design decisions including environmental impact and analysis. It is used mainly to calculate the embodied carbon at the design phase with the integration of Naviswork, as shown in Fig. 7.

6.1 Creating a model for a sharing system

The common system model can be interpreted using a software application that enables multiple players involved in a construction project (client, architect, engineer, contractor) to work in a connected and coordinated manner. The information and data can be collected, managed and disseminated among multiple teams in a secure, clear and controlled manner, which is critical for the development of BIM projects. Using the BIM360 platform provides participants with the ability to exchange information in an easy and manageable way, as shown in Fig. 8 and Fig. 9, respectively.

6.2 Coordination process

Collaboration and coordination are very important at the design phase to produce a model satisfying the design requirements and environmental analysis. This helps the designer and decision-maker to choose the best materials with low carbon and create environmentally friendly constructions. The initial milestone in the creation of any model started by the architect when he/she determines all the levels and main units is called the central model because all other disciplines will build their workflows on this milestone. Coordination occurs between all parties involved in the project and then the embodied carbon calculations are added for consideration by the designer and decision-maker in all design requirements at the early stages. Compatibility between Autodesk products such as Revit and Naviswork facilitates decisions by the project designer and decision-makers on the environmental impact of a project.

To start the coordination process, the different files are combined through Revit, as shown in Fig. 10, by linking all the files to get a single model.

To satisfy the research objective, the Dynamo script has been divided into six categories as shown in Fig. 11, which are:

- Category 1: identify all equations of the material embodied carbon calculations using Excel (depending on the SE2050 commitment to net zero).
- Category 2: this category works as a screen to determine the considered inputs parameters.
- Category 3: data input.
- Category 4: environmental analysis (calculating the material embodied carbon emissions).
- Category 5: integration of disciplines.
- Category 6: output and decision-making.

7 CASE STUDY

To investigate the proposed workflow, a scientific centre located in Cairo, Egypt was chosen as a case study. The proposed workflow and Dynamo script focused on emissions related to different materials (depending on the SE2050 commitment to net zero) during the design phase. The scientific centre includes a main building (B1) with an area of *c.* 2900 m^2/floor in addition to other small buildings. B1 consists of a basement, ground floor and three typical floors, about 16 m in height and 215.46 m perimeter. The basement has a capacity of up to 50 cars, the ground floor has a separate entrance with some green areas. The first, second and third floors are for administration, scientific research, and

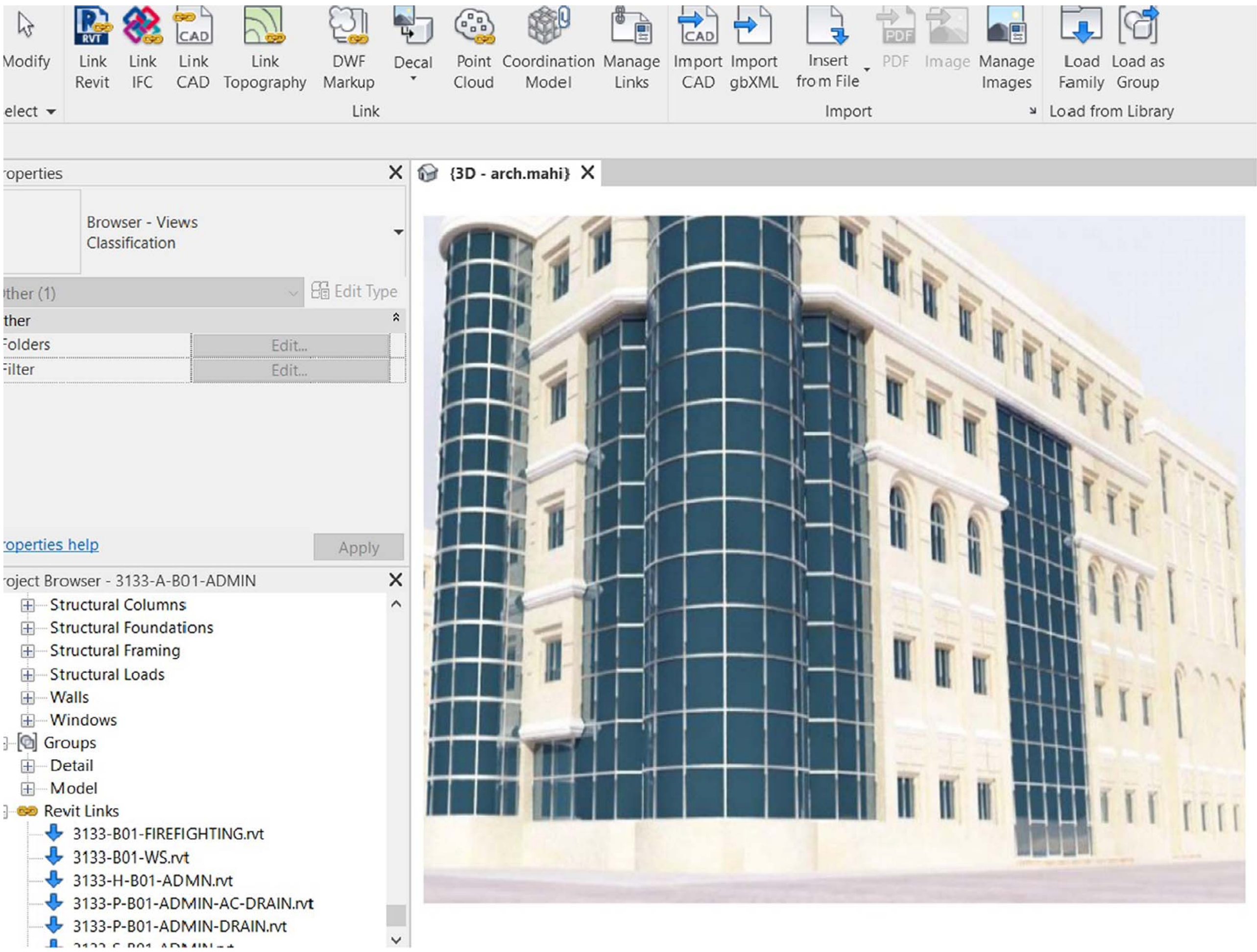


Figure 10. *Design coordination process using Revit.*

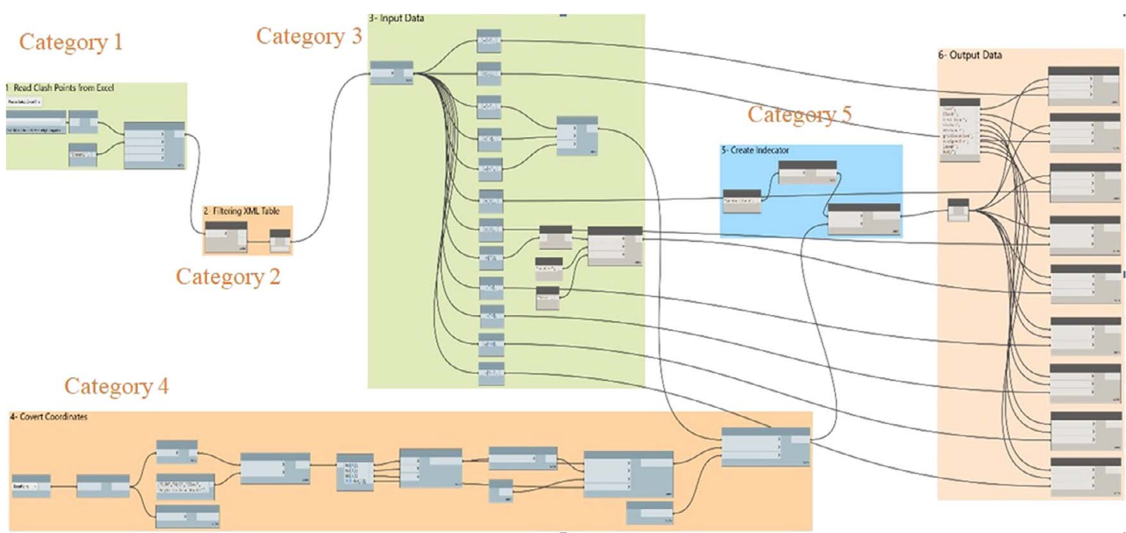


Figure 11. *The components and categories of the Dynamo script.*

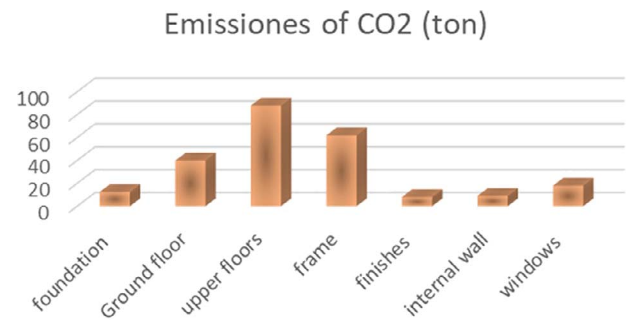


Figure 12. *Results of the case study.*

laboratories, respectively. An OPC with 60% waste substitute and 60% recycled steel reinforcement is used for the ground floors, upper roofs and internal walls. Ordinary bricks for cladding and PVC frames for windows are used in this construction—all of these materials are defined and their properties are uploaded to Revit (family). Figure 12 shows the results of using the proposed workflow and Dynamo script to determine the number of emissions (ton) of CO_2 for the scientific centre. The results show that most CO_2 emissions in the case study come from the reinforced concrete skeleton (foundation, ground floor, upper floors and frame). Whereas the finishes, internal walls and windows are a small source of CO_2 emissions. About 80 tons of CO_2 were emitted by the upper floors, which were the largest source of emissions, and 3.543 tons of CO_2 from finishes, which were the smallest source of emissions in this study.

To validate the proposed workflow and the Dynamo script, the previous case study was resolved using an online open-access calculator called 'Embodied CO_2 Estimator' as shown in Fig. 13. Figure 14 shows the percentage of difference between the results of the two methods (proposed workflow and the online open access).

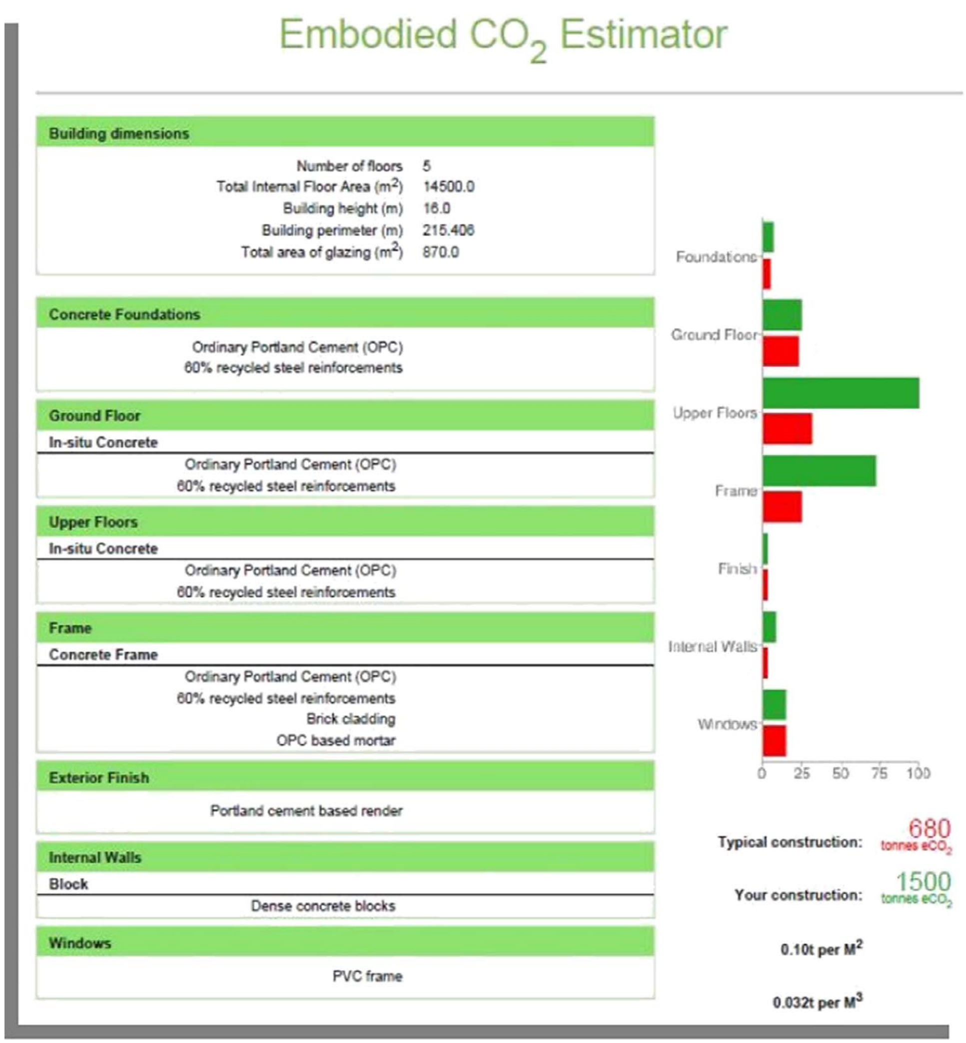


Figure 13. *Results of the case study.*

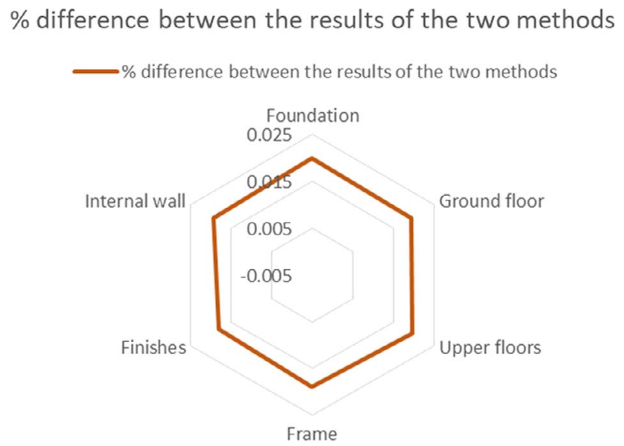


Figure 14. *Percentage of the difference between the results of the two methods.*

8 LIMITATIONS OF THE RESEARCH

All limitations of the research must be considered and made known to everyone who will make use of it. A summary of the most important limitations from the authors' point of view is as follows:

1. The calculations of the embodied carbon depend on SE2050's commitment to net zero. This point must be made clear to all users of this research.
2. The proposed workflow and Dynamo script created for this research were tested in construction buildings only.
3. The calculations of the embodied carbon in this research were made at the design phase only.

9 CONCLUSIONS AND RECOMMENDATIONS

This study introduced a tool to assist the designer and decision-makers to consider the environmental analysis and impact in their designs (calculations of embodied carbon related to SE2050 commitment to net zero) using BIM and its components. This will push the designer to choose suitable sustainable, green and low-carbon materials, which are available in the industry market now. Put another way, this also will encourage researchers and centres of research to create new materials from their surrounding environment, which will help the construction industry to become environmentally friendly. All these efforts will be reflected worldwide by decreasing climate change, global warming, emissions, and so on. However, the limitations of this research are that it considered and calculated only one type of emissions (CO_2) with only known materials. In addition, all the calculations are at the design phase, which the authors recommend improving, as well as more studies to include all the embodied emissions at all phases of a construction throughout its life cycle using the same model.

The main conclusions are summarized in the following.

- It is important to undertake an environmental analysis, especially of carbon emissions during the design phase, which will reflect on the overall timeframe and cost of the project.
- Spreading the knowledge of the integration between different compatible software adds value and new products.
- Increasing the benefits of using BIM in other non-traditional ways.
- Improvement of programming branch and AI in the applications of constructions and civil projects.

In brief, the work in this study could be expanded to include the following:

- Improve the proposed model by linking it with GIS to determine the location of the project and determine factors for each country to refine the results.
- Upgrade the proposed workflow and the script to include all civil projects, not only construction buildings.
- Expand the proposed workflow and the Dynamo script to include calculations of embodied carbon at other phases of the life cycle of the building (construction phase, operation and demolition phase) not just in the design phase.

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DATA AVAILABILITY

All data are available within the manuscript.

AUTHOR CONTRIBUTIONS

Conceptualization, A.E (Ahmed Ehab). Methodology: M.A(Majed Alzara); Software: A.E and M.A, Valdation, A.M.Y. (Ahmed. M. Yosri).; formal analysis, E.C. (Erdem Cuce); Investigation, A.E., A.M.Y, and M.A. Resources A.A(Amer Alruwaili). and S. M (Sayed M Eldin). Data curation, A.M.Y.; Writing: A.E, A.M.Y, M.A.

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