2025 European Conference on Computing in Construction
CIB W78 Conference on IT in Construction
Porto, Portugal
July 14-17, 2025

A FRAMEWORK FOR MEASURING THE DIGITAL CARBON OF DESIGN WORKFLOWS

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Abstract

Digitalisation of workflows in the construction industry brings environmental costs. Digital carbon measurement approaches are not tailored to digital design workflows. Existing research on digital design workflows and digital decarbonisation is used to inform the design of a framework for measuring carbon emissions of design workflows. An evaluation of the framework is presented which demonstrates the framework can be used to calculate CO2e from digital design data storage and transfer. Our research increases awareness of the digital carbon footprint of construction projects and our framework can support organisations to adopt sustainable digital practices to align with Net Zero targets.

Introduction

Globally, it is believed the construction sector and built environment combined, account for approximately 38% of worldwide carbon emissions (United Nations Environment Programme and Yale Center for Ecosystems + Architecture, 2023) and amongst nations committed to Net Zero, there is a recognition of the need to decarbonise this sector to attain their Net Zero commitments (Arogundade et al., 2024). Whilst modern approaches to collecting information about buildings across the supply chain offer unprecedented data resources for analysing and improving processes, the carbon impact of digitalisation is yet to be fully acknowledged. Reducing the digital carbon footprint should feature in sustainability strategies; however, government policy and recent technological innovations do not address the digital carbon footprint of organisations (Jackson and Hodgkinson, 2022).

Even though digitalisation is considered one of the keys to promoting decarbonisation throughout the building life cycle, its negative contribution to climate change and global warming is undeniable. The responsible use of data is of great importance for reducing carbon emissions associated with digital activities and reversing this negative impact, however, many organisations are not aware of the environmental cost of their own digital practices. The vast amounts of unused or outdated data stored, generally without tangible benefits and resulting in data waste, consumes significant amounts of energy causing unnecessary carbon.

The BS 7000-4:2024 Design management systems and BS EN ISO 19650-1:2018 provide guidelines for supporting digital workflows in the design, construction, operational and deconstruction phases of buildings. During a building lifecycle, many thousands of data exchanges occur. Each information supplier or consumer across the supply chain has different data requirements depending on their roles, disciplines, established customs and practices, and their selected software tools. Often data does not migrate through all phases and can be poor and inadequate for reuse by corresponding stakeholders (e.g. contractors, facility managers, or clients) or other systems receiving the data, leading to data redundancy and duplication (Rogage and Doukari, 2024). Data collected, stored and processed through normal business processes that goes unused for any other purpose is known as dark data (Gartner, 2022). Jackson and Hodgson (2022) claim over 55% of all data produced by organisations is thought to be dark data, in the construction sector studies have shown this figure to be as much as 95.5% (Hill, 2017).

This opens opportunities for researchers to explore new methods for capturing, monitoring, and reporting on the carbon footprint of digital processes which can support organisations in developing sustainable digital practice strategies. We define the digital carbon footprint as the carbon impact resulting from collection, processing, storing and communication of information and technologies used to carry out these activities. We propose a framework for measuring the carbon footprint of digital workflows in the design phase of construction that is used to explore the questions:

1. How can organisations capture and measure the carbon impact of their digital workflows?

2. How effective is the proposed framework for measuring carbon emissions in digital design workflows within the construction industry?

The objectives that address these questions are to: research digitalization of the sector; research existing methods for measuring the carbon footprint of digital assets; develop and evaluate a framework for measuring the carbon footprint of digital assets created during digital design workflows.

We begin with a literature review to identify the research problem, then we develop and evaluate a framework for measuring the carbon impact of digital assets. Exploring the relation between digital transformation and digital decarbonisation in design, our paper identifies the pressure on the construction industry to meet Net Zero targets, whilst highlighting how digitisation design processes generate excessive amounts of unused data which brings an environmental cost. We also demonstrate the lack of practical tools for measuring the carbon impact of digital processes. We consider the design stage of a building lifecycle and BIM workflows and technologies for collecting, processing, storing and communicating data. Our key contribution is a framework for measuring the carbon footprint of digital design workflows which can be used to motivate industry practitioners to research and apply best practices for optimised data management.

Research Method

A literature review was conducted to understand the impact the construction sector has on carbon emissions and how this is being mitigated through digitalisation. Further literature was explored that considers how the carbon impact of digital assets can be measured. From this research we developed a framework which integrates Jackson and Hodgkinson's data carbon ladder (2023), with an adapted version of BS 7000-4:2024 Design management systems and BS EN ISO 19650-1:2018 combined to capture the design workflows. We evaluate the framework to understand its validity as a tool for measuring the carbon emissions of 4 digital assets commonly found in a digital workflow during the design phase of a building. Figure 1 provides a view of the research workflow carried out. The design phase of buildings life cycle provides the scope of the study as it is the phase where most data related to the building production is generated and is the ideal phase for developing a more sustainable digital ecosystem.

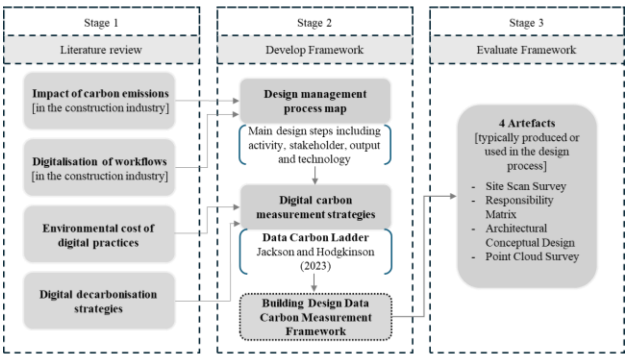

Figure 1: Research workflow

Related Work

Decarbonising the construction sector

The Net Zero agenda instigated several areas of research and innovation around digitalisation approaches for decarbonising the sector. The use of BIM for supporting sustainable building design and operation is well documented (Khahro et al., 2021). BIM combined with AI has been used to support classification processes for understanding carbon impact of materials (Abdulkadir and Rogage, 2024). Early research by Rogage et al. (2019) considered how BIM processes could enable interoperability between building design and IoT data for managing building performance. Advancements in IoT, BIM and AI technologies have led to a growth of digital twin research for capturing, monitoring and simulating a range of building activities from reducing energy consumption through to supporting retrofit design (Ohueri, Masrom and Seghier, 2024). Further research has considered the use of digital twins for modelling and monitoring construction processes onsite to support more efficient construction approaches onsite (Saif et al., 2025; Rogage et al., 2022). Whilst digitalisation is significantly impacting carbon footprint reduction in construction (Royal Institution of Chartered Surveyors, 2023), the carbon impact of digitalisation in the sector is still to be considered. Furthermore, there lacks evidence of a specific methodology for capturing and measuring the carbon impact of digitalisation processes in the sector.

Digitalisation of the construction sector

While the sector is attempting to address sustainability concerns, an ongoing digital transformation of the sector has also resulted in greater use of more cloud-based digital workflows in construction and design processes, which has aided the industry in several ways (Samuelson and Stehn, 2023). These have included: improved collaborations amongst project stakeholders (Merschbrock and Munkvold, 2015); enhanced efficiencies from using digital tools to streamline repetitive or mundane tasks (Sepasgozar et al., 2022); increased accuracy of digital designs and construction plans; better data management (Huang et al., 2021; Jin et al., 2023); cost savings (Sepasgozar et al., 2022), and safety enhancements (Luo et al., 2024; Ye et al., 2023). During this digital transformation there have also been better integration of sustainability efforts where for example, energy modelling software and use of related digital tools can aid evaluation of building designs for energy efficiency, and environmental impacts of project delivery (Fonseca Arenas and Shafique, 2023).

Digital workflows in the construction sector

A digital workflow involves a sequence of tasks and processes which are facilitated by digital tools and technologies to improve data management, as well as operational efficiency and productivity. In the context of the project-based construction industry, cloud-based digital workflows can streamline various design, planning, and execution stages of a construction project for stakeholders employed at different companies, when working together as part of a temporary project organization. Whilst the likes of mobile applications

(Jowett et al., 2023), and construction site monitoring (Rao et al., 2022) technologies such as drones and, sensors represent the types of digital tools and technologies used during site-based execution stages of construction projects, this work focuses upon digital workflows found within the design stage of construction projects. Some digital tools and technologies employed in this stage include: Building Information Modelling (BIM) which allows the representation, analysis, and modification of designs across digital platforms in real-time; project management software helps teams to plan, communicate, share, and manage tasks and schedules digitally; Use of electronic/digital document management (Jaskula et al., 2024) for centralized storage and easy sharing of project documents within firms, or across them if using Common Data Environments (CDEs); and Virtual and Augmented Reality technologies help create immersive experiences for design reviews (Seyman Guray and Kismet, 2023).

Impact of digital workflows on sustainability

Whilst digitalisation presents many benefits, the process of digitalisation in many cases increases the carbon footprint of an organisation (Jackson and Hodgkinson, 2022). Digitalisation is resulting in unprecedented amounts of data being captured, stored and processed through advanced data analytics approaches such as AI (Alsop, 2024). Increases in data storage and processing are possible through the evolution of cloud computing. Cloud computing reduces the financial cost of hosting and storing data to organisations, however, the ability to store and process larger datasets results in more energy use which subsequently increases greenhouse gas emissions (GHG) with digitalisation accounting for around 4% of GHG emissions (Teuful and Sprus, 2020).

Jackson and Hodgkinson (2022) estimate 2.5 quintillion bytes of data are produced every day by organisations and this number is rising exponentially. On average employees waste up to 20% of their time a week duplicating data (International Data Corporation, 2018). Within the sector, on average, some of the largest infrastructure projects result in around 130 million emails, 55 million documents and 12 million workflows (Snyder et al., 2019). It is estimated approximately only 0.5% of this data is used. Creating quality, reuseable data has the potential to reduce costs associated with employee time and storing and processing data, whilst also reducing the carbon footprint of digital activities. The process for capturing and storing data should be a critical consideration of IT sustainability practices.

Strategies for digital decarbonisation

Whilst much of the research around carbon reduction focuses on tools to support sustainable practices, there is little published on how to measure the carbon footprint of data and digital workflows. Lannelongue, Grealer and Inouye (2021) present their Green Algorithms tool for measuring the carbon footprint of the computation of algorithms. Mersy and Krishan (2023) propose an automated life cycle assessment tool, carbon provenance, for assessing the embodied and operational carbon footprint of data collected from sensor devices stored on the cloud. Varying approaches to calculating the carbon cost of kWh per gigabyte are available (Adamson, 2017; UK Government, 2023). But none of these tools offer a practical approach to measuring a digital artefact from the process of data capture through to storage and communication.

Jackson and Hodgkinson's data carbon ladder enables the diagnosis of each data item across a timescale (2023). This tool sets out the steps of data acquisition, storage, processing, reporting and visualization. The first step involves the data capture process which could involve a) creating new data; b) importing existing data; c) linking to data at source, a hybrid of a) and b), or a) and c). Once data is acquired then data storage needs to be considered. Data not accessed in real-time at source creates a carbon footprint for data storage. Data not hosted on the device that is accessing data required to be transmitted across a network has a further carbon impact. The carbon footprint of the data analytics method is captured, and the impact of data visualization and reporting activities are measured.

The data carbon ladder provides details of how to calculate the carbon footprint at each step based on the size of the data being captured. What is presently lacking in the construction industry, is an approach to capturing and measuring the digital footprint of activities that generate data throughout typical building design processes.

A digital decarbonising approach for architectural design practice

Playing a pivotal role in every construction project, design management focuses on processes, resources, information, organisational infrastructure, planning, and the array of compliance checks and distribution of responsibilities that enable the design to happen whilst maintaining the programme and collaboration at the heart of each activity (British Standards Institution, 2024). The design process is cyclical and consists of different methods put together to suit the nature of each project, requiring interaction among the stakeholders with many feedback loops (Best, 2015). As a data-intensive process, it generates a large amount of data exchanged and used throughout the entire building life cycle.

Due to their iterative, non-linear nature, particular client and user needs, changing market conditions and customer preferences, design processes are much more dynamic and fuzzier and are difficult to standardise (Best, 2015). In addition, based on changing industry trends towards more digitalisation, the amount of data generated in the design process is increasing compared to traditional tools and techniques. However, the design process has shown some signs of standardisation in recent years.

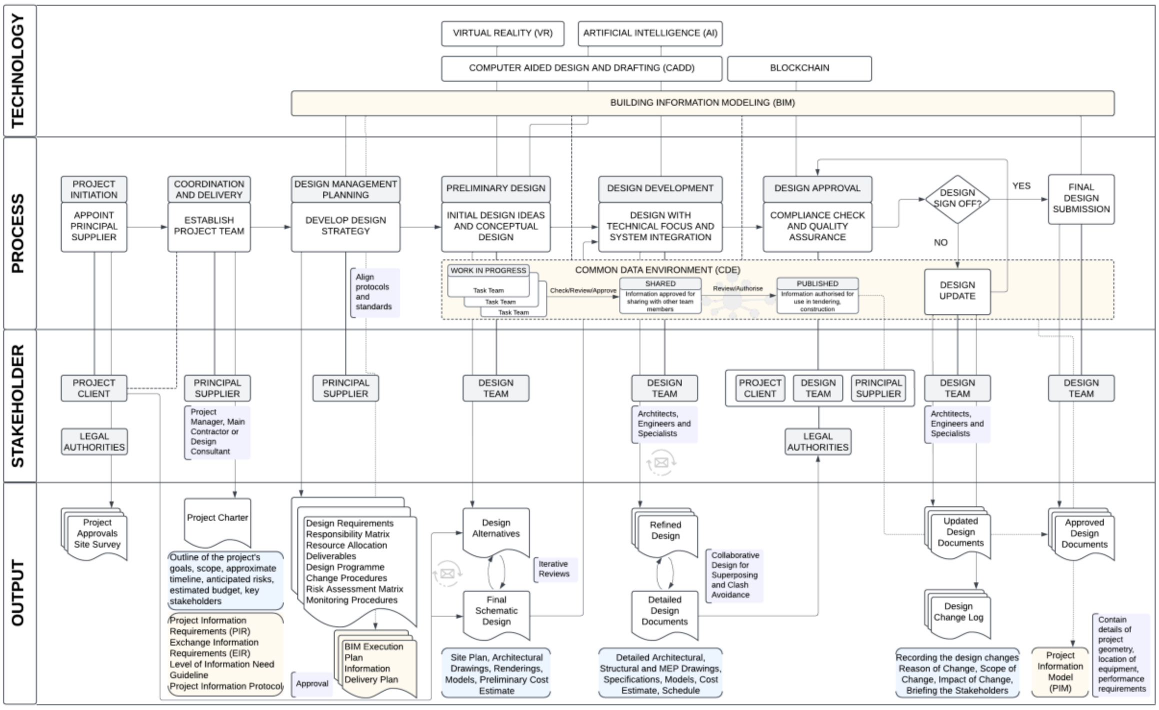

Figure 2: Design process map (adapted from BS 7000-4:2024 Design management systems, British Standards Institution, 2024 and BS EN ISO 19650-1:2018)

Design processes are the main driver for information capture and data management in construction projects. When delivering information in the building project development lifecycle using BIM, the ISO 19650 series has been a lead standard adopted by industry regarding BIM implementation and data management across projects. While workflows will vary depending on the project's organisation, the typical design process will involve creation of specific documents specifying information requirements and digital processes. Key documents created to support ISO 19650 data management include an exchange information requirements document, a BIM execution plan, a project information protocol, a common data environment plan, the level of information need guidelines, an information delivery plan, and a project information model.

Figure 2 outlines the process map of design management, incorporating also BIM information management. Depending on the project delivery method chosen; roles, responsibilities, collaboration, and decision-making dynamics in the design phase change. Here, we present the simplified design process, mainly based on the traditional method, with a concern to highlight the essential design workflows and outputs for assessing digital carbon.

Experiment

We adapted Jackson and Hodgson's (2023) data carbon ladder to capture and measure the carbon footprint of typical data artefacts produced through building design activities. To do this we have created a framework (Figure 3) aligning the design processes identified in Figure 2 on the X axis against the data carbon ladder steps on the Y axis. We selected 4 artefacts typically produced or used in the design process. This study aimed to evaluate the practicality of applying the data carbon ladder approach to a variety of digital artefacts that were developed as part of independent design workflows, that is we selected items from different parts of the workflow shown in figure 2 but they were not all part of the same project workflow. They were digital artefacts that the research team had access to from different design projects.

Much of the data produced during the design process is co-created with teams across organisations and stored on a cloud-based CDE. Some items may be created on-premise with a version shared on the CDE. Data items go through many iterations of revisions, with stakeholders being alerted of changes through email and communication platforms such as Microsoft Teams. We acknowledge these activities have a digital carbon footprint but are outside the scope of the current study, which is to understand how to use the ladder to measure the digital carbon footprint of a design artefact. The four data items used were: i) site scan survey; ii) responsibility matrix; iii) architectural conceptual design; iv) point cloud survey. Out of the 4 data items we considered, 3 are documented through the perspective of a single organisation taking the role of lead designer. The 'site scan survey' data capture completed by an external organisation resulted in the 'point cloud model' used by the lead organisation. We chose this data output as we wanted to demonstrate measuring the digital footprint of an imported data item.

Data Carbon Ladder		Design Process														
		Data CO2	Project Initiation	Data CO2	Co-ordination and Delivery	Data CO2	Design Management Planning	Data CO2	Preliminary Design		Data CO2	Design Development	Data CO2	Design Approval	Data CO2	Design Submission
Visualisation	Visual dashboard Text report		E57 file				Excel spreadsheet, Word doc. or PDF		BIM file e.g. IFC or proprietary format	BIM file e.g. IFC or proprietary format						
Data Analytics	Descriptive Prescriptive Informative Predictive Cognitive		Informative				Informative		Informative	Informative						
Data Storage	At-host storage On-premises storage Data Centre (cloud computing)	38kg CO2e	Cloud			0.0002kg CO2e	Cloud	1.61kg CO2e x2	Cloud	Cloud						
Data Velocity	Batch, Real-time, Near Real-time, Static		Static				Static		Near real-time	Static						
Data Size	_mb, _gb, _tb, _pb		5Gb				29kb		200mb	200mb						
Data (dis)Aggregation	Import data set Use data set at host Aggregation of data sets		Created on-premise				Created on-premise		Created on-premise	Import data set						
Database / Set	Design requirements Responsibility matrix Architectural drawings Structural drawings etc.		Site scan survey				Responsibility Matrix		Architect's concept design	Point cloud survey						

Figure 3: Building Design Data Carbon Measurement Framework

The site scan survey was a static file, created and stored by the host organisation that provided informative data. The file was a 5Gb point cloud produced in the E57 file format. The responsibility matrix was a 29kb static Microsoft Excel file that provided informative data, created on-site by the lead designer and shared via a cloud-based CDE. The point cloud survey was a modified version of the scanned survey which was processed to reduce the file size for ease of transmission and processing by the lead designer. The survey file was reduced to a 200mb point cloud file on-premise by the survey company and shared with the lead designed on the cloud. The compressed point cloud file was converted into a 200mb Autodesk Revit file by the lead designer and stored and shared on the cloud. For this study we calculate the carbon footprint of the final version of the file and do not include the cost of any file iterations. Each data artefact was added to the ladder and the kg of CO2 of each ladder step was calculated using Jackson and Hodgson's (2023) approach (1). Our calculations are based on 5 years of storage (1,826 days including one leap year) and data transfer, we do not consider processing costs which would need investigation in future research. For data storage on premise there is no carbon cost. The cloud server carbon calculation formula is:

$$(\text{Size of file in Gb x } 0.00075kWh) \text{ x time period of storage in 24 hours x number of days to be stored x } 0.23314\ (CO2) = \text{CO2e for data transfer and storage costs.} \qquad (1)$$

Results

Figure 3 shows the 4 data artefacts mapped against the carbon ladder and the resulting CO2e. The site scan survey represents a typical file generated during the project initiation phase; the responsibility matrix at the design management phase and the point cloud survey and architect's concept design at the preliminary phase. Table 1 shows the calculations for each data item.

As the largest file the site scan survey typically produces the most CO2e resulting in 38kg. The responsibility matrix produces the least at 0.0002kg and the point cloud survey and architect's concept drawing both produce 1.5kg CO2e. The total digital carbon footprint for the 4 data items equates to around 41kg CO2e.

Table 1: Digital carbon footprint calculation

Data Artefact	Calculation	CO2e
Site scan survey	(5Gb x 0.00075kWh) x 24hrs x 1826 days x 0.23314 CO2	38kg
Responsibility matrix	(0.000028Gb x 0.00075kWh) x 24hrs x 1826 days x 0.23314 CO2	0.0002kg
Point cloud survey	(0.2Gb x 0.00075kWh) x 24hrs x 1826 days x 0.23314 CO2	1.5kg
Architect's concept design	(0.2Gb x 0.00075kWh) x 24hrs x 1826 days x 0.23314 CO2	1.5kg

The results demonstrate a framework for capturing and measuring the carbon impact of digital workflows, the effectiveness of the framework evaluation is considered in the discussion.

Discussion

Digitalisation is advancing efforts to support sustainable practices in the sector, whilst also contributing negatively to global warming. Sustainability strategies currently don't consider the impact of digitalisation and to date there is no formal methodology for measuring the carbon footprint of architectural design processes. We propose a framework for measuring the carbon impact of some typical activities in the architectural design process. We address this gap in knowledge through the design of the Building Design Data Carbon Measurement Framework. The framework builds on existing knowledge from Jackson and Hodgkinson's (2023) data carbon ladder and extends it to include the design workflows adapted from BS 7000-4:2024 Design management systems and BS EN ISO 19650-1:2018. Our early stage research demonstrates that the framework can be used to calculate the carbon footprint of artefacts at different stages of the design phase which addresses our first research question.

The framework has the potential to support design consultants such as architects to evidence their IT strategy for reducing their digital carbon footprint i.e. by measuring the carbon footprint before and after sustainable practices are employed. The framework can help design consultants identify spikes in CO_2e and consider how processes can be refined to reduce emissions. For example, through reducing communication flows to reduce time and waste associated with unnecessary digital exchange and storage.

In response to our second research question we consider the effectiveness of the framework for measuring carbon emissions of digital design workflows. In our study the framework was used to calculate the carbon emission of 4 artefacts. These artefacts were static and we only considered the final version of the each file. In this case the framework lends itself well to calculating the CO_2e of each data item.

Recommendations and Future Work

We acknowledge that this work is not without limitation. For example the architect's drawing would go through many iterations of design changes, whereas we only captured the final file. Another limitation is that we selected 4 files that were not part of the same design workflow, furthermore we only used files from 3 phases of the 7 stage workflow. A more rigorous evaluation would look to map outputs from the same design workflow at each stage, and capture each iteration. Future research could also consider the carbon footprint of different data analytics. Further research is also required to understand the embodied carbon footprint of data.

Whilst the data carbon ladder approach works well with a single data source it is difficult to map the methodology onto typical architectural design processes. For example, some processes involve many iterations of data revisions producing additional communications and the ladder lacks steps for capturing this. This offers opportunities for developing the framework further to support design processes. The architectural design process is also just one perspective of the digital carbon footprint created on a building project. Building projects involve many stakeholders carrying out many activities across the building design lifecycle. This opens future research opportunities for exploring the digital carbon footprint across the entire design management process of a building.

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