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Adoption drivers and barriers of Building Information Modelling (BIM) in Europe

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ABSTRACT

Building Information Modelling (BIM) enables time, cost, and materials savings in building design and construction. However, the promise of BIM is yet to be realised. We assessed the current state-of-the-art in BIM adoption and use, identifying both barriers and opportunities across six dimensions defined by the PESTLE framework (political, economic, social, technical, legal, environmental). We combined market survey, literature review, and new insights from 41 expert interviews with architects, consultants and constructors across 11 European countries. We find BIM is used principally by larger firms as a design and data-processing tool to enable collaboration between project partners. BIM's value proposition is primarily to streamline construction processes not improve resource efficiencies. Barriers to BIM adoption include interoperability issues, split incentives and value chain fragmentation, and weak economic incentives particularly for small firms. In the medium-term we find two important drivers of more widespread BIM adoption. First, institutional investors in the commercial buildings sector are increasingly pushing green certification standards for which compliance is demonstrated by BIM. Second, whole building lifecycle emission regulations for buildings mandated by the EU from 2030 will require BIM calculations. Four pioneer Northern European countries already have similar emission limits in place. Under realistic assumptions, we estimate material savings enabled by BIM in new building construction could deliver 21–31% embodied emission reductions after 10 years.

1. Introduction

Buildings and construction account for about 41% of European greenhouse gas emissions [1]. Building information modelling (BIM) can help identify material and operational efficiencies in buildings particularly at the construction stage [2]. BIM is a generic name for software models used in the design, build, operation, maintenance, refurbishment, reuse and demolition of buildings as well as other infrastructure such as roads and tunnels.

BIM has support in European policy as a tool for providing data on buildings [3], for reducing design and build costs through process and material efficiencies [4], and potentially for reducing buildings' embodied carbon emissions [5]. The European Construction Technology Platform (ECTP) have estimated BIM can achieve cost savings up to 13–21% from design and construction and 10–17% from operations [4,6].

This study explores actual BIM adoption barriers experienced by architects and construction firms that mean these potential benefits are not being fully realised.

1.1. BIM: What it is & what it does

BIM is defined as "a set of processes, tools, and technologies capable of producing, using, and updating a virtual model of information throughout the life cycle of the building" [7]. There are numerous BIM platforms such as ArchiCad, Autodesk Revit, Infurnia, Navisworks, Tekla and Trimble. Multiple applications or tools can run using BIM. Many incorporate third party data that are self-created or purchased, such as tools to calculate points for green certification schemes [8]. Data standards have been established to enable interoperability between BIM and tools, although data losses remain an issue [7,9,10]. The man BIM dimensions and applications are shown in Table 1. A full description of BIM and related tools is provided in Appendix A1.

Kreider and Messner [11] distinguish 18 use cases for BIM grouped into 5 categories describing the handling and use of building information: gather, generate, analyse, communicate, realise. For example, the 'realise' category includes use cases for building information to fabricate, assemble, control, and operate the building. Charef and Emmitt

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Table 1
BIM dimensions & applications.

BIM Dimension	Potential Applications
level 3	3D design co-ordination & input from different skills & trades. Clash detection. Calculation of material quantities. Bills of Materials production.
level 4	includes all level 3, plus time element, e.g.: Phased ordering and planning.
level 5	includes all level 4, plus costings, e.g.: Costing of Bills of Materials.
level 6	includes all level 5, plus end-of-life, e.g.: Recycling and reuse planning.

[12] extend this to 38 BIM use cases, of which 11 inter-relate to similar aspects of building design and management, 19 are potential enablers of circular economy approaches during the building's active lifecycle (prior to decommissioning), and 8 relate to buildings' end-of-life and waste management.

Designing a building in BIM creates a coherent set of drawings that can be updated automatically when a design change is made in one area. Coherent drawings lead directly to early detection of design inconsistencies and accurate Bills of Materials. This can help reduce materials waste. BIM allows multiple professionals to collaborate on individual copies of the model simultaneously before combining the results and checking for inconsistencies. In addition to collaboration, BIM facilitates document management, time saving in a multi-user environment, virtual reality to assist design, and the ability to use mobile devices on site [13]. When combined with job scheduling, BIM offers an advanced, integrated control mechanism to ensure timely delivery of projects. These time and cost efficiency use cases for BIM apply more to multi-actor, multi-firm jobs than single architect-contractor relationships.

1.2. BIM at different stages of the building lifecycle

BIM has applications throughout the building lifecycle from design through construction, refurbishment, and end-of-life. Giorgi et al. [14] describe BIM as "an enabling tool for monitoring the use of resources during the building lifecycle, sharing information between operators, and stimulating reuse potential".

However, architects and owners prioritise immediate transactional value from using BIM rather than material or energy efficiencies over the full building lifecycle [15]. Consequently, most scientific studies on BIM relate to the design, planning and construction phases of buildings [16–18].

BIM also has potential to facilitate material- and energy-efficient refurbishment [19]. However, its use at this stage of the building lifecycle is limited even though refurbishment costs can amount to over half the building's total lifetime cost [9]. BIM's relative newness means most buildings needing refurbishment do not have a BIM, and tendering processes mitigate against costly investment in creating a new BIM [20].

BIM can also be applied to construction, demolition and waste management [7,10,21]. This includes BIM functionality for designing for disassembly particularly for temporary buildings or internal fit-outs [22], and aiding the incorporation of existing structures into renovation designs. BIM can further assist reuse of existing end-of-life building sections, particularly carbon-heavy structural load-bearing elements (e.g. [23,24]).

1.3. Aim of this study

BIM can enable process efficiencies in building design, build and management, with resulting benefits along not just economic dimensions but also environmentally by reducing buildings' material footprints. However, these benefits are preconditioned on BIM being in widespread use throughout the building value chain and lifecycle.

Technical and scientific literature on BIM has been concerned with its development, tools, and novel use cases (e.g., [25]) consistent with *potential* contributions to business and societal goals including a more circular economy. However, few studies have sought to understand BIM's *actual* contributions to financial, time, material, energy, or carbon savings in building construction by taking the perspectives of architects and construction firms – the value chain actors whose use of BIM is a precondition to benefits being realised. This gap in scientific literature is explicitly noted by Çetin et al. [16] and Walasek & Barszcz [26]. Ahmed et al. [19] make the same point in this journal in relation to BIM at the refurbishment stage: "In theory BIM energy retrofitting framework works, however, in practice this is yet to be fully realized." In the absence of evidence from firms' perspectives, firms which don't adopt BIM *are assumed* to lack information, education and process understanding in order to explain why market potentials are not being fulfilled [27–29]. This is particularly the case in smaller firms among which BIM adoption is lower [30].

Charef and Emmitt [12] and Giorgi et al. [14] interview BIM practitioners (among other stakeholders) to understand BIM use cases in relation to the circular economy but they focus on BIM's potential contributions rather than adoption barriers which must necessarily be first overcome. Kanters [31], Cruz Rios et al. [32], and Kirchherr et al. [33] all conduct studies using expert interviews with building value chain actors including architects and construction firms to understand firms' perspectives on circular economy challenges, but they do not focus specifically on BIM. Pereira et al. [34] in this journal use systematic review to understand BIM capabilities but in relation to energy rather than material efficiency, and without clearly distinguishing firms' perspectives.

In this study we characterise the current state of BIM use among architects and construction firms in different European countries and market segments. Our aim is to identify the drivers and barriers of BIM adoption as a basis for projecting its future potential contribution to material savings and embodied emission reductions in building construction (Box 1).

2. Literature review

We review scientific and grey literature in three main areas: current barriers to BIM adoption; BIM use in lifecycle materials, energy, and emissions analysis; the BIM regulatory landscape. Details of our literature search terms and methodology is provided in Appendix A2.1. From this literature review we identify knowledge gaps that our research design aims to fill.

2.1. BIM current adoption, and barriers to adoption

Rates of BIM adoption vary significantly across Europe [35]. Some European countries including UK, Denmark and Italy have made BIM mandatory for government-procured public building contracts and have developed standards governing its use [14]. As a result the Nordic countries and the UK are market leaders in the use of BIM [35]; see also Fig. 1.

Around two thirds of European architects' firms use 3D computer assisted design (CAD), but the overall BIM adoption rate is estimated at 31%, with significant variation among firms of different size [36]. 80% of European architects work in 1 or 2-person firms; 54% of all architectural work is residential and over 50% of all work is refurbishments. Larger firms write their own BIM tools in response to perceptions of need or customer demand, potentially to gain a competitive edge [37]. But creating a BIM is costly: any savings accruing to the clients during design and construction are unlikely to benefit the architects directly [26]. Architects may adopt BIM if they foresee cost savings in their own practices, but BIM is not perceived to save office time or money [20].

Several other barriers to BIM adoption by architecture, engineering

Box 1
Definitions & Terms.

AEC	architecture, engineering and construction
BIM	building information modelling
CAD	computer assisted design
EBPD	Energy Performance of Buildings Directive
LCA	lifecycle analysis or lifecycle assessment (for estimating emissions over a building lifetime)
WLC	whole life carbon

and construction (AEC) firms have been identified [38–40]. This include difficulties implementing BIM [41,42] and devising protocols for its use [15,43,44].

Adoption and implementation issues principally relate to the systematic precision needed to make use of BIM tools (Table 1), requiring working practices within the firm to be reorganised during implementation [45]. This changes job roles and perceptions of seniority [38], typically favouring those with digital skills and away from those competent in established pre-BIM practices. This changes power relations and invisible knowledge infrastructures within firms [38,46].

Efficient use of BIM also requires sharing model data with contractors: the short-term project-by-project culture in the AEC industry and an unwillingness to share information for perceived competitive reasons [38] mitigates against collaborative practices and reduces incentives for BIM adoption [47,48].

2.2. BIM, materials savings, and embodied emission calculations

BIM lifecycle analysis (LCA) tools create inventories of the energy and materials needed across the supply chain and value chain for a building in order to calculate resulting greenhouse gas emissions. Various studies apply BIM-LCA to buildings at either design stage (e.g. [49]) or construction stage (e.g. [17]).

BIM offers a data foundation that can be used for narrowing, slowing and closing material loops in line with circular economy frameworks [14,16], though few studies involve real-world cases [50]. Materials savings are primarily determined at the design stage [7,10,15]. Studies of BIM use for clash detections that avoid rectification work emphasise labour savings rather than materials savings (e.g. [51,52]).

Few studies quantify purchased materials which are wasted during the build. Available statistics commonly aggregate construction and demolition waste into a single category. One study in the Netherlands found that the amount of building material wasted was 1–10% of the amount purchased, with a further 9% by weight ending up as construction waste [53]. These provide a reference point for the magnitude of potential material savings from BIM use. A firm survey found tender prices that reflect both labour and materials costs can be reduced by 6–10% using BIM [50].

A South Korean study assessed two buildings where the design was revalidated by BIM, achieving savings of 4.3% and 15.2% of materials

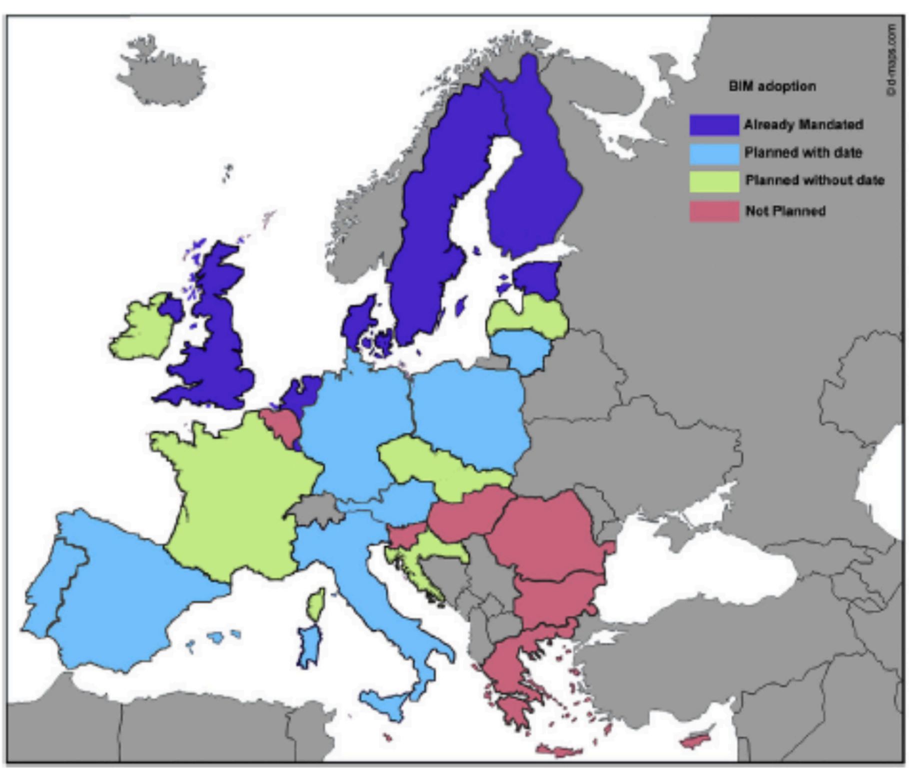

Fig. 1. Extent of BIM Adoption across Europe as of May 2017.
Source: [35].

[54]. As building types vary across international geographies, these results are not directly transferable to Europe.

BIM-LCA also facilitates iteration of building design towards minimising both embodied energy and projected operational energy over the building lifespan [55,56]. 'Embodied energy' refers to energy used in the extraction and fabrication of components and to energy used in the construction process. Emissions embodied in new buildings are many times the annual operational emissions [57]; most also occur immediately rather than over a building's life. Material selection, component reuse and prefabrication are key for reducing embodied energy [2,4,57]. These are largely independent of BIM use.

Embodied carbon (or greenhouse gas) emissions are derived from the materials and their embodied energy. Embodied emissions data for each building element is held in individual Environmental Product Declarations (EPDs). Using BIM for LCAs requires automated data exchanges with an EPD database, although data interchange is recognised as a BIM weakness [55,58].

Relatively few studies focus on BIM's use for helping meet emission reduction or circular economy goals. Those that do tend to assume BIM is an enabler of cost savings and material efficiencies as a basis for energy and emission savings [2,4,59].

2.3. BIM and the regulatory landscape

The focus of legislation in EU member states has been on optimising building performance to improve operational energy efficiency [3]. This has led to a 32% reduction in operational carbon emissions since 1990 but only 6% fewer embodied emissions (Green Alliance [60]). Regulations on operational energy usage stipulate maximum levels of heat loss per square metre through walls, floors and ceilings. Architects and constructors can achieve these levels by selecting materials with specific properties; BIM is not necessary.

However, in 2024 the revised Energy Performance of Buildings Directive (EPBD) gives member states until 1 January 2027 to set regulations for limiting and reporting on "whole life carbon" (WLC) for all new buildings by 1 January 2030, and those over 1000 m^2 by 1 January 2028 [5]. Whole life carbon (WLC), also referred to as "lifecycle global warming potential" is an indicator that quantifies the carbon emissions attributable to a building throughout its full life cycle, including both embodied and operational emissions. These encompass the manufacturing, transportation, construction, use, and end-of-life phases of buildings.

LCA will be necessary to report on a building's whole life carbon. This will likely boost BIM adoption. Although LCAs are possible using 3D CAD, they are easier from BIM as it holds more data on each building element. The EPBD does not specify whether calculations should be carried out at planning or completion, or both.

Prior to the EPBD for all EU member states, legislation limiting embodied emissions or whole life carbon emissions in buildings has already been passed in four countries in the past five years: Denmark (BR18), France (RE2020), Sweden (Swedish Climate Declarations) and Netherlands (MPG); see Table 2 for details. All differ in methodology, coverage and exemptions. However, well before 2030 these limits will have legal force: buildings exceeding the limit can be denied occupation permits (see also [61] for the Swedish case). Norway, Finland, Belgium and Iceland are developing similar regulations [62]. Certain cities like London also require whole life carbon calculations in larger developments, but as yet there is no legal limit (London Assembly [63]).

2.4. BIM knowledge gap: firms' perspective

Overall, scientific literature on BIM has been concerned with its development, applications, use cases, and potentials. There are fewer studies on BIM adoption drivers and barriers from firms' perspective, as noted by Çetin et al. [16] and Walasek & Barszcz [26].

An exception is Charef and Emmitt [12] who interview 20 BIM

Table 2
Current regulations limiting buildings' embodied emissions from materials and construction in four EU member states.

Country	Timeline	LCA calculation notes	Exemptions	Key Sources
France Reg = RE2020	From 1 Jan 2022 for residential & office buildings, 2023 for all buildings. Limits tightened in 2025, 2028 and 2031.	Life cycle emissions (embodied and operational). Result expressed in $kgCO_2e/m^2$. Over 50 year life. 'Dynamic LCA': future emissions are discounted, so embodied emissions in the build has greater impact. Assessed at permitting and completion.	Industrial buildings.	Ministere de la Transition Ecologique [64,65]
Denmark Reg = BR18	LCA submissions necessary from 2023 for all buildings unless $<$ $1000m^b$ (due 2025).	Limit: 12 $kgCO_2e/m^2$/year for all buildings $>$ $1000m^2$, lowering to 8.6 $kgCO_2e/m^2$/yr in 2025. Over 50 year life. Modules A1-A5*. Single assessment at completion. The limit ratchets down further every 2 years.	Buildings $<$ $1000m^2$ until 2025. Renovations. Plumbing and electrical works.	[66]
Sweden Reg = Swedish Climate Declaration	Submissions necessary against building permits issued from 1 Jan 2022. Legal limits enforced from 1 July 2025.	Life cycle emissions (embodied and operational). Limit as $kgCO_2e/m^2$/year set in 2025 at 75% percentile of reported values in 2022. Over 50 year life. Modules A1-A5*. Plans to lower limit in 2030 (25% reduction), then 2035 and 2043. Single assessment at completion.	Operational emissions until 2027.	[67], One Click LCA [62], Storenso.com, (2022)
Netherlands Reg = MilieuPrestatie Gebouwen (MPG)	From 1 Jan 2018. Residential buildings from 1 July 2021.	Limit: expressed as € environmental damage**: €1.0/m^2/year, reduced to €0.8/m^2/year from 2021. Covers fabric of new building plus any component replacements. Over 50 year life. Single assessment at planning.	All exempt except new offices and residential. Excludes operational emissions.	[68], Knowledge [69]

* Modules of whole life carbon assessments: A1 Raw Material Supply; A2 Materials Transport; A3 Manufacturing; A4 Materials Transport; A5 Construction & Installation processes. (B1-B5 cover materials during building use; B6 is operational energy for heating, cooling and powering the building; C1-4 covers end-of-life).
** Environmental damage valued at the social cost of carbon and the result expressed in €/m^2/year. Includes measures other than CO_2e, such as material toxicity and ozone layer depletion.

practitioners and related experts to understand BIM use cases that could contribute to circular economy. They identify a range of relevant new BIM uses including: digital mock-ups for end-of-life; materials passports; project databases; data checking and updates; circularity assessments; materials recovery processes; and materials banks [12]. However, in their case they were interested in how BIM could overcome barriers to circular economy practices, rather than the barriers to BIM adoption which is a necessary precondition to its beneficial use cases.

Giorgi et al. [14] used semi-structured interviews on the drivers and barriers of circular economy with 38 stakeholders from 5 countries in the value chain for buildings including policymakers, investors, designers, manufacturers, construction companies, and waste managers. Others have similarly used expert interviews to understand architects, constructors, and other stakeholders' perspectives on circular economy practices and challenges [31,32,33]. However, none of these firm-oriented studies has focused specifically on BIM.

Reliable adoption data on BIM is sparse and generally based on market surveys for which respondents are self-selecting. For example, a 2023 industry survey suggests that BIM's penetration rate is 70% amongst construction professionals, but two thirds of responders were consultants and so not representative of the AEC sector [70]. Other data showed only 5% of small business adopters have implemented level 3 BIM (e.g. cost and material saving functionality such as clash detection and Bills of Materials) [71].

We address the use to which BIM is actually put and the value the users see in it, ranging from being an essential business tool in large firms to a costly irrelevance for many smaller firms [17,56].

3. Research design

We use a series of semi-structured expert interviews with architects and construction firms to test and extend findings from the literature review on real-world adoption and use of BIM, and BIM's potential contributions to material, energy, and carbon emission reductions.

We answer the following research questions:

RQ1. What are the drivers and barriers of BIM adoption among firms for building design and construction?

RQ2. What contribution can BIM make to reducing whole life carbon emissions from buildings if it becomes widely adopted?

3.1. Method: Expert interviews

We conducted interviews on our research questions in two tranches: (i) architects and construction firms in EU countries; (ii) architects in the four countries in which whole life carbon legislation has already been introduced (Denmark, France, Sweden, and Netherlands). Interviews in the first tranche covered BIM adoption drivers and barriers from the practitioners' perspectives and experiences. Interviews in the second tranche focused specifically on BIM use in whole life carbon (WLC) assessments in pioneer countries to help understand the wider potential for BIM once the revised EPBD enters into force.

3.2. Sample & sampling strategy

Expert interviews aim to cover the main sources of variation in understanding and experience of BIM. As noted in the literature review, this varies as a function of firm size and country context. These provided the two dimensions of our sampling frame. We use a simple stratification to split a practical number of interviews across different firm types and sizes, and country groups (Table 3; full details in Appendix A2.2). Small architect firms account for 80% of architects and 41% of turnover, medium architect firms 17% and 41%, and large architect firms 3% and 18%, respectively [36]. The sample covered each market segment.

In total, we contacted and followed up with 114 firms, leading to 41

Table 3
Expert interview sample characteristics and identifier labels (upper rows) and summary statistics on use of BIM (lower rows).

	Tranche 1 interviews on BIM adoption drivers and barriers				Tranche 2 interviews on BIM use in whole life carbon assessments
Country group	**Small architect (1–2 people)**	**Medium architect (3–9 people)**	**Large architect (>10 people)**	**Constructors**	**Architects, Valuers & Others**
BIM use already mandated	A1 (UK) A2 (Netherlands) A3 (Norway) A4 (Sweden)* A5 (UK)* A6 (UK)*	A8 (Netherlands) A9 (Netherlands) A10 (Norway)* A11 (Netherlands) A12 (Netherlands)	A14 (Netherlands)	C1 (UK) medium builder C2 (UK) international consultancy C3 (UK) large builder C4 (UK) building data automation firm C5 (Netherlands) large developer C6 (Netherlands) family builder	L1 (Denmark) large architect L2 (Denmark) architects association L3 (Denmark) large architect L4 (Denmark) large architect L5 (Denmark) large architect L6 (Sweden) small architect L7 (Sweden) small architect L8 (Sweden) medium architect L9 (Sweden) financier & developer L10 (international) climate bonds L11 (UK) property valuer L12 (UK) property valuer
BIM mandate planned but not yet implemented	A7 (Croatia)	A13 (Ireland)	A15 (Latvia) A16 (Latvia	C7 (France) medium sized BIM consultancy C8 (Spain) tier 1 contractor C10 (France) multinational contractor	
No BIM mandate planned **		A18 (Slovenia)	A17 (Belgium)	C9 (Belgium) BIM software start-up C11 (Greece) multinational contractor	
Total n of which..	7	7	4	11	12
do not use BIM	4	3	0	2	–
use BIM level 2	2	1	1	0	–
use BIM level 3	1	3	3	4	–
use BIM level 4	0	0	0	3	–
n/a (consultants)	–	–	–	2	–

Notes: * short interviews; ** prior to EPBD entering into force.

interviews (Table 3).

We contacted European architects through internet-accessible registers of professional body memberships. This sampling frame omitted certain countries (e.g. Lithuania) where the publicly available register does not include contact details, and Finland where there is no public register in English.

Construction firms and contractors are not members of registered bodies in the same way as architects: there is no central list in each country to select from. We contacted construction firms at trade shows, through snowball sampling (recommendations from architect interviews), and through institutional contacts (see Appendix A2.2 for details). Few interviewees specialised in a single sector (residential, commercial, infrastructure).

Both literature and our initial interviews found that relatively few BIM models were used in construction, fewer were passed to new owners, and of these only a small proportion would be used in facilities management [72]. Accordingly, we did not seek to recruit facilities managers for interviews.

Our 41 interviewees included multiple users of BIM and related tools: architects, engineering consultancies, project managers, constructors and building facility managers.

In the first tranche of interviews, architects in the sample are labelled A1-A18 and constructors C1-C11. In the second tranche, architects, valuers and other firms are labelled L1-12 (as this second tranche was focused on lifecycle emissions).

Table 3 also summarises the interviewees' current use of BIM levels 2–4 with more functionality (and complexity) at higher level (see Table 1 for explanation). Architects using BIM level 2 used BIM to draw but did not make use of the data associated with the drawings. The constructors not using BIM included a household name UK housebuilder. The constructors using BIM level 4 scheduling were all multinationals, with the clients prepared to pay for additional third-party software licences.

3.3. Data & analysis

We use a topic guide to semi-structure our interviews, covering the key themes identified from the literature review related to our research questions. The full interview guide is provided in Appendix A3.

The majority of interviews were conducted via Microsoft Teams, with some interviews by phone, other media platforms, or in person.

All interviews were in English which was generally the interviewee's second language, resulting in variation in how words were used. Accordingly, we avoid analysis of specific words and word counts, and in our analysis we pay particular attention to context, following guidelines for expert interviews set out by Meuser & Nagel [73].

We transcribed the interviews before summarising and coding the interview data in Nvivo.

For our analysis we use the PESTLE framework which is widely used to understand how Political, Economic, Social, Technological, Legal, and Environmental factors affect an organisation's strategy or practices – in our case, BIM adoption. The PESTLE framework is useful for systematically identifying pressures, weaknesses and opportunities for organisations in both current and potential contexts [74,75]. In their study of BIM use cases for the circular economy, Charef & Emmitt [12] similarly use a PESTLE-type framework (with Organisational instead of Legal) to organise their analysis of barriers – but of circular economy applications of BIM rather than BIM adoption and use *per se*.

We use a thematic coding template derived initially from applying the PESTLE framework to the literature then iteratively developing the categories and codes based on the data. Specifically, top level codes were initially established deductively based on the PESTLE categories (see Appendix Table A2.6). The coding template was then inductively expanded upon through the data analysis process. Additional codes, iteratively identified within each category, were added and the original codes sub-divided. For example, an initial code of 'BIM Skills' in the 'Social' category was expanded into codes for 'BIM Training', '3D CAD Training', and 'Education'.

The final set of thematic categories and codes is provided in Table 4, rank ordered by the number of interviews in which codes were mentioned.

Within PESTLE, the line between 'Political' and 'Legal' can be blurred. We included political and legislative support within 'Political' and compliance with regulations in 'Legal'.

4. Results

We first present and discuss our main findings from the expert interviews on the drivers and barriers of BIM adoption, using the individual dimensions of the PESTLE framework as way of structuring the data, before providing an integrated perspective.

4.1. Political

In the 'Political' dimension of PESTLE, we cover EU regulations, BIM mandates and rules, and whole life carbon regulations (see Table 4 for thematic codes).

BIM adoption rates have stalled over the last 5 years [70]. Interviews support this: either firms were BIM-reliant or they rarely, if ever, used it. Only interviewee A11 planned to implement BIM in the future (to enable tendering for municipal work). Two others (A7 & A13) had BIM capability but constructor indifference meant little opportunity to use it. Most firms work in market niches that may not require BIMs for publicly funded buildings (C4, C8). No interviewee mentioned the revised EPBD with its mandate for whole life carbon (WLC) assessments for all new buildings by 2030 [5].

Interviewees in Belgium, Latvia and Slovenia (A16, A17, A18) expected their governments to follow France, Denmark, Sweden and the Netherlands in passing building lifecycle emission regulations. They regarded BIM as necessary to enable detailed embodied emission calculations, although 3D CAD can be used (C3). Almost all buildings are designed digitally and lifecycle emission regulations incentivise use of the model for environmental purposes, otherwise embodied emission calculations are infrequent and only advisory. Constructors are resistant to change (A2, A7, A12) unless required by regulations. In countries where current regulations need an as-built model on building completion this places significant new demands on constructors (e.g., investment, training, work practices), many of whom currently work from architects' 2D plans and do not use or update models at all.

While there are many imperfections in BIM calculations and process (see 'Technical' section below), building lifecycle emission legislation has 'changed the landscape' of the industry (L4) and concentrated minds in ways which would not have happened otherwise (L5). For example, suppliers are now producing more Environmental Product Declarations (EPDs) on embodied emissions in building components and materials (L4, L9). This is viewed positively (L4, L5, L9; see also [67]). However, concern was expressed that municipalities have no expertise to check the resulting LCA-derived estimates (C4, C5, L4). For example, in Spain, legislation requiring submission of a BIM was passed without industry support: many councils do not have software licences to open the model (C8). Moreover, there is suspected manipulation of EPDs by manufacturers (L2). This lack of verification is potentially serious: if there is no difference between buildings with apparently low and high lifecycle emissions then credibility will be undermined (L2). Borderline illegitimate practices in tendering have already been experienced (C5).

Both Denmark and Sweden have introduce embodied emission regulations with relatively weak initial limits that did not force immediate changes in material use or construction methods. In Denmark the initial limit of 12 $kgCO_2e/m^2/yr$ was higher than the prevailing norm (10 $kgCO_2e/m^2/yr$) (L3). In Sweden, the limit in 2025 is to be set at the 75th percentile of reported lifecycle emissions from 2022 (Table 2). Both cases allowed time for firms to prepare for compliance, including BIM

Table 4
PESTLE framework themes used to code interview data, rank ordered by frequency of occurrence (number of interviews, and number of references within interviews). Codes in bold in each PESTLE dimension were the original codes in the interview guide.

	# interviews	# references		# interviews	# references
POLITICAL			**TECHNICAL**		
regulations, government support			**prefabrication, calculations, tools, design, data**		
regulations	6	11	design	10	14
			designing issues	8	11
ECONOMIC			comms (technical)	6	8
value, costs, savings, strategy			consultants	6	9
demand	9	11	digital divide (roles)	6	7
cooperation	6	9	digitalisation	6	7
better control	5	7	no calculations	5	8
efficiency	5	7	BIM use or not	4	7
strategic	4	5	building maintenance	4	4
tangible cost	4	5	discipline	4	5
better design	3	6	methods	4	11
business models	2	2	standards	4	7
marketplaces	2	3	tool writing	4	4
intangible values	2	5	comms (people)	3	4
other	2	3	data transfer	3	3
size	2	3	workflow	3	4
skills shortage	2	2	approach	2	3
digital divide (economic)	1	1	age	1	1
embodied C savings	1	1			
LCA economic	1	1	**LEGAL**		
speed	1	1	**clients, model ownership, reuse**		
use of 2D	1	2	building regs	13	19
			government work	6	8
SOCIAL			BIM ownership	4	4
BIM skills, BIM use issues, digital divide, practices			use of consultants	2	2
BIM training	6	10			
no interest	6	8	**ENVIRONMENTAL**		
education	5	5	**reuse, design for disassembly**		
decisions	4	6	clients (sustainability)	3	3
interest	4	6	design for disassembly	3	3
varying use	4	6	awareness	1	1
BIM other	3	6	operational C calcs	1	1
culture	3	4			
other	3	4			
3D CAD other	2	2			
levels 4&5	2	2			
3D training	1	3			
client choices	1	1			
digital divide (social)	1	1			
country differences	1	2			
qualifications	1	1			

adoption. Mandatory lifecycle emission limits in France will force material changes from 2028 (C10). This will in turn affect roles and responsibilities within the sector. In practice one LCA value is needed at design/planning stage, and one from an as-built BIM on handover and building occupation. In most countries, these two LCA calculations will be carried out by two different organisations: architects and constructors, and even the architects may not have been responsible for selecting all the materials (C9, L2). Constructors, often untrained and inexperienced in using or amending BIMs, may need to complete the as-built model. This faces skills barriers (see 'Social' section) (L2).

4.2. Economic

In the 'Economic' dimension of PESTLE, we cover the value of BIM to firm processes and business models, including through realisable cost and time savings (see Table 4 for thematic codes). Interviewees' perceptions and experiences varied across different firm types and market segments.

Adoption drivers of BIM cited by architects include coordination and communication between designers and specialists, better design, better control of the design, more accurate tendering, and more efficient working practices. Adoption barriers raised included system costs, time investment in both training and building design, and lack of demand from clients – even large clients needed educating about the benefits of BIM (C11; see also [38]). Both architects and constructors see the potential for BIM uptake to help with more accurate Bills of Materials, less rework, and so material savings, as well as higher speed (A3, A11, A13, C6, C8, C11).

Adoption barriers were emphasised in particular by interviewees from small firms. Notably, the economic benefits of BIM are intangible and difficult to convert to monetary value, but the costs are more directly experienced. In an economic environment in which each project must make a standalone profit, this mitigates against both experimentation with BIM and collaboration with project partners with whom the relationship will end once the project completes (C8).

Larger architect firms were generally unequivocal in their support of BIM's communication and coordination benefits (A2, A3, A15, A16). One interviewee gave an example of BIM supporting projects with over 100 cooperating designers across 70 disciplines and trades (A17). Another interviewee remarked that "the business is run on BIM, and that time saving, money saving or client demands for BIM are irrelevant, the business will use it anyway" (A8). Others commented on the efficiencies and better control gained through BIM: in error reduction (A15); in reduction of information losses on data exchange (A11, A15); in more accurate material specification (A2, A3, A13); and in improved (though unspecific) efficiency (A7, A16, A18).

In contrast, smaller architect firms saw less economic value in BIM. All but one (A6) small-firm architect interviewee used 3D CAD or BIM, but most identified significant barriers to BIM use. Reasons included lack of demand from clients (A3, A13, A15), no constructor demand for data beyond the 2D drawings and 3D visuals from a CAD system (A1, A7, A13), and time spent learning new software (A1, A5, A10, A11): "it's a time thief" (A10), "too fiddly" (A1), "cumbersome" (A6). 80% of EU architects work in 1–2 partner firms and their staple is the 54% of the market that is single homes (new builds, extensions, renovations) [36]. Creation of a project from new takes more time in BIM (A7). Creating it by adapting a pre-existing design is quicker if BIM is set up to do this (A9, C6). More than compensating savings are expected in time and material during the build [70], but these savings generally do not accrue to the architects, although this depends on architects' roles which vary by country and by firm. Vertically integrated firms (design and build) do not have this split incentive problem.

The picture on economic incentives for BIM use from contractor interviewees was different from architects. Not all contractors working for large firms use BIM, some simply take 2D printouts (A14) and the benefits of BIM to constructors are not always apparent. One interviewee said: "to my mind, there's no point in having a BIM that isn't also connected to construction program and cost" (C2). The benefit of BIM was undermined if it could not be continuously compared with actual progress during the build. Newer tools for constructors include systems utilising a mobile camera to automatically compare build accuracy to the schedule and plan in BIM. This offers more reason for contractors to use a BIM, but is unlikely to result in material efficiencies through waste reduction (C9, C10). BIM enables offsite modular construction (A8): this saves materials as well as time, but for a constructor, quantifying the material savings remains difficult (C8).

4.3. Social

In the 'Social' dimension of PESTLE, we cover the skills and training implications of BIM for personnel, the effect of BIM on roles and responsibilities both within firms and across industry networks (see Table 4 for thematic codes).

Earlier papers observe that disciplined use of BIM is essential [76,77]: this is reinforced by interview findings. Decisions such as allocation of responsibilities, setting key immutable design coordinates and the level of detail in the planned model are initial requirements (A3, A15, A17, A18). Internal company procedural manuals are key to control of the process (A15). Furthermore, in some EU states the division of responsibilities for the BIM between different entities in the supply chain is documented and codified (A8, A18).

In some areas, there is clearly a BIM skills shortage (A7, C11). For small-medium sized firms in countries where BIM adoption is low, using BIM as a communication and cooperation tool is difficult (A7, A18) due to network effects: the benefits of BIM increase with user numbers. Adoption by smaller builders is slow (A1, A2, A7, A12, A18). Constructors have enough work and cannot see reasons to change their materials or methods (A2, A7). Resistance to change current practices is high [41,78].

There are two 'digital divides' detectable in architects' interview data: within firms and between firms. Younger architects develop into more skilled software users (A18) once they have been trained to firm standards (A14, A15). Some firms also spend money on external training (A9, A15, A16). In Latvia, technical school trainees are trained on BIM principles (A16), but this seems to be exceptional (A3, A7, C8). The digital divide between firms is evidenced in literature [70], and interviews showed larger firms use more software and have more training, though much of it in the sample of interviewees was done on-the-job and in-house (A1-A10, A14-A17).

Within larger architects firms, there is a tangible split between 'designers' and 'technical architects', the latter using BIM in more detail than the designers (A15, A16). In medium and large firms the technical architects outnumber the designers (A8, A15), and "you need a very skilled architect overseeing the process, though the younger ones may be more fluent in the computer skills" (A16). "There is a danger that the company leaders get left behind with the technology and the detailed knowledge of the processes in their own firms" (A16), as "the technical skills are held by [technical architects]" (A8). This impacts the power structures within the business: "it's always discussion like, OK, the technical drawers [make] a big part of the income of the company" and "Still, we are with 30 people and we are with eight or nine architects and the rest of the company is the case managers and technical drawers? So they have a bigger vote" (A12).

The construction sector demonstrates a large digital divide between the majority who did not use 3D CAD or BIM beyond the printed output from an architect's model (C1, C3, C9, C10), to large firms integrating the latest video-to-BIM comparison systems for progress chasing (C8) and self-developing IKEA-like building kits-and-diagrams to turn construction sites towards assembly operations only (C10). The higher-tech operations were focusing on speed to save money: secondarily, there are material savings from better cutting plans and less rework (the former rated at 7%-10% of materials cut in factories) (C10). The high-tech initiatives tend to de-skill the build process: recognising that workers tend to have a "low level of education and in some cases they are not very fluent with the language either" (C8, also C2). Only one constructor was trying to move from paper to digital-only on-site: a Dutch family firm with a very stable workforce (C6). This requires giving workers the right level of detail in small models which update continuously and can be interrogated simply on small devices (C5): they do not access the main model. At the higher tech end, interviewees in France and Belgium reported difficulties getting the BIM as they required it from architects, to the extent that they rebuilt their own (C9, C10) or became heavily involved in its making (C7). Two interviewees from different southern European states flagged serious cultural issues with BIM adoption as construction practice is to make money from cost overruns and problem rectification. The constructors in these states will not welcome the control and transparency that BIM brings and are unlikely to implement it swiftly or thoroughly.

When smaller buildings are covered by lifecycle emissions legislation, smaller architects and constructors will be impacted. Interviewees were divided on probable outcomes: views ranged from the need for small architect firms to specialise in order to survive (L1) to thoughts that in the near-term there will be better software and more consultants, and with the primary responsibility for LCA compliance resting with the contractor (at completion stage) the impact on architects will not be too significant (L3). This ignores the large culture change for small contractors and a significant investment and training need across the AEC sector [79].

There is awareness that building design, structural calculations and embodied emissions calculations should be done simultaneously, and some firms are creating software to do this (L8). Only one firm interviewed did so (A14). On finalisation it used a consultancy to recalculate the structural analysis for liability reasons. The more technically minded firms often had intellectual property concerns about sharing the models beyond collaborating firms or consultants (A9, C9). Use of a structural consultant to calculate a building's structural integrity transfers legal responsibility out of an architect's firm (A2, A8, A9). It also places a barrier in the way of iterating designs towards optimisation of embodied and operational emissions at any realistic speed, as the consultant is used only after the design is finished and additionally may not use BIM (A14).

The handover of a building to the new owner is a time when the use of the BIM may cease. This varies greatly within and between states, with clients of large firms in certain states (Latvia, Netherlands) apparently far more likely to use the digital twin to 'manage the building' than others (A2, A16, A17, L8). 'Managing the building' generally means using the data for maintenance (to look up building or parts details) rather than operational energy, as BIM does not lend itself to automatic input from sensors (C6). Maintenance engineers would require experience of BIM to use it (A18), which would not be normal.

More user-friendly software is being written to update the BIM or to extract data from it and import it into facilities management software (e.g. Glidertech.com, Kabandy.com), but data operability and interoperability issues generally curtail BIM use after construction completion. Most small firms do not supply clients with anything more than pdfs electronically (A1, A12) and some did not even do this (A2, A6), though it is possible to export data from 3D CAD (in IFC format) if it is needed occasionally (A10, A11).

As staff need BIM training to access BIM data, the BIM is not generally used in facilities management unless the constructor is also managing the completed building (C5, C6). Skilled constructors can tailor output from BIM for various facilities management systems, if the manager is chosen in advance and their system known (C8). Unskilled constructors may pass on a BIM of limited completeness and usefulness (C9) and not all facilities managers can work with BIM anyway (C6). Essentially, the BIM holds vast amounts of detailed relationship data between building elements, but the facility managers only need spatial data plus a look up facility to check parts details for maintenance or replacement purposes. It appears that normally much or all data is lost on handover of the completed building.

BIM data can be used in lifetime building management. However, the inflexibility of data handling in BIM, together with the training and access controls required to use it, make it unsuitable as a basis for facilities management software. This commonly leads to a break point in the data trail with apparent loss of much of the building information which could otherwise have greatly assisted planned maintenance programs and reduction of replacement parts. While this break point is starting to be addressed by third party software companies, it implies that many buildings coming to the end of their first lives will continue to be BIM-less.

4.4. Technical

In the ‘Technical’ dimension of PESTLE, we cover BIM vintages, data handling, functionality, tools and applications (including LCA), and accuracy (see Table 4 for thematic codes).

The heart of BIM software is old, as highlighted in this open letter from the Nordic architects associations to Autodesk, owners of the market leading Revit software:

> *Every day digital design leaders around the world wrestle with software, which at its core is twenty years old and incapable of the potential of multi-core computing and graphics power designed to process within today's real and virtual workstations. Project productivity in architectural and engineering practices is hit daily because of the lack of scalability and product performance, which then requires sophisticated and practice specific ‘work arounds’. (Nordic Architects Letter* [80]*).*

Interviewee A1 (UK small firm; non-BIM user) made the same point: the software is too old and needs a complete rewrite to modern software standards.

Although the level of design functionality has improved markedly in the last 10 years (C10), BIM software does not lend itself to rapid input/output of data necessary to iterate a design to minimise lifecycle emissions (L2), collect real-time building management data (C6) or interface with a non-BIM trained user (C9).

There is no single way to use BIM: setting up the model differently is widespread (C10) and when combined with firms’ different data inputs, normally precludes the model from being used for the full range of functions such as design parameterisation (C6), Bills of Materials (A7, C5, L2) or scheduling (C7). Most architects using BIM thought it made them better architects and designers (A7, A15, A16) although few initially design directly into BIM. A common practice is to first design using pen and pencil, or applications such as Sketchup, Rhino or Allplan, and transfer these rapidly into BIM (A2, A11-A14, A16, A17). Linked virtual reality tools allows designers to ‘walk around’ inside the building and improve its design (A15, C5), though it’s also a sales aid (A16, C6).

BIM functionality is highly dependent on tools that analyse exported data. The amount of exportable data held on each building component distinguishes BIM from 3D CAD (A8, A16), and enables a variety of consultants to perform calculations/operations in which they are specialist (structural, heat loss, thermal comfort and many others) (A2, A7, A8, A12, A15, A16). Using consultants is partly about sharing responsibility (A15), but also demand is insufficient to employ specialists even in larger firms (A8).

In contrast to earlier papers (e.g. [58]), none of our interviewees emphasised data handling as a major issue. Uploads and downloads, though imperfect, work well within products from the same software house: “You can do it like five times per day and you can … control this project really easily” (A16). In contrast, for firms not using advanced data functions, the limited digitalisation of 3D CAD still enables apartment block construction (C3).

Tools written in-house are significant in larger businesses for process control and time saving (A1, A14, A16, C11), for example, different tools for calculating and reporting regulatory requirements for the 3 areas of Belgium: Flanders, Wallonia and Brussels (A17). Digitalisation of data also allows more options to be considered, and weight and stresses to be calculated more accurately. It does not override professional judgement, which ultimately determines the use of materials (A16). The technical difficulty of running BIM accurately leads to a lack of trust in the data and a reluctance to take decisions based on it (C4). Inability to produce Bills of Materials precludes gaining one of the most obvious benefits of BIM, as these are known to be highly accurate (A3). So BIM models are generally “not as sophisticated as you would think or hope” (C2).

Embodied and lifecycle emission calculations using LCA tools require a strict methodology to make results comparable: these rules are still developing. For example, the Danish method is set out in LCA Byg (lcabyg.dk), and many software firms are writing LCA interfaces to BIM (L3, L5). Nevertheless, there is still a ‘big debate’ on methods (L2, L4), including what it should cover (e.g., groundworks, foundations, kitchens, mechanical, electrical and plumbing are likely to be 11–15% of a building’s total embodied emissions [81] and what level of detail it should cover (e.g., pipework under 25 mm diameter) (L2, L3). There are discussions around credits for design for deconstruction and for use of recycled materials, the latter currently included at zero value (L2, L4, L5). These will all need defining before limits can be enforced and its potential fulfilled. The recent EPBD permits methodologies to vary by country to adapt to local conditions [5].

4.5. Legal

In the ‘Legal’ dimension of PESTLE, we cover compliance with codes and regulations, risk and liability issues with new materials, and insurance (see Table 4 for thematic codes).

Whilst acknowledging the importance of governments promoting BIM, the usefulness of BIM as a control measure is currently limited (A16). Interviewees assert that building codes are all satisfied by submission of 2D pdfs supported by relevant calculations. In many countries hand drawings suffice. However, for certain government agencies in some countries a BIM model is required for certain building types (examples from interviews include Latvia, Norway, Slovenia and the UK). Respondents were unclear (or dismissive) about authorities ability to read a BIM, though Latvian interviewees were positive about their municipalities determination to get a BIM education (A15 & A16).

Although BIM enables new lower emission materials and reused building elements, but these pose legal or regulatory issues.

First, standards and current regulations governing (for example) concrete and laminated wood products are quite specific. Concrete excludes new alkali activated cements (expensive, but on average 50% lower embodied emissions [82], and laminated wood must exclude recycled wood. Regulations generally act as a brake on the use of new materials (L2) and regulatory flexibility to enable experimentation with new materials varies across Europe (C10). Significant material changes require the approval of products, including bio-based ones, which cannot currently be shown to last 50 years or so.

This creates a second issue: accepting new or reused products for insurance purposes (L5, [83]). If steel beams from a building are removed, individually subjected to testing, and resold, an insurance company will need to cover them. This is currently only a nascent market. It is difficult to find trios of owners, architects, and constructors willing to incorporate such products (L1, L2, L3).

Third, careful removal of products from buildings for reuse, such as steel beams, takes significantly longer than demolition and lengthens overall construction time, which is an economic problem [84].

4.6. Environmental

In the 'Environmental' dimension of PESTLE, we cover material substitution (e.g. to wood), offsite construction, modularity and other BIM applications that provide environmental benefits such as green certification (see Table 4 for thematic codes).

Structural elements hold 45–55% of total embodied emissions in a building [85–87]. BIM enables building designs and constructions with novel materials, rightsized elements, and materiallly-efficient onsite practices. All these can help deliver lower environmental footprints (A2, A14). However, sustainable materials (including bio-materials) are seen as more expensive (C1, L2) [88]. Their relative pricing may change if they become higher volume and the EU's carbon taxes are applied to imported cement, due from 2027 (L8).

Interviewees were specifically asked about using wood or more specifically cross-laminated timber (CLT) as a structural material. Several use it (A2, A3, A8, A10, A18) but it can be specified from a 3D CAD system; BIM is not required for straightforward shapes (A3, A10, A12, A18). Using Denmark as an exemplar, CLT is not seen as a standard material, and there is a large concrete lobby (L3). The closest CLT factories are in Sweden and Austria (L4), signalling supply issues if CLT use becomes widespread as a means of limiting a building's lifecycle emissions (L5). No alternatives to concrete other than using structural wood, steel or low emission concrete were suggested in interviews (C5, C10, L5) despite specific questioning. 'Low emission concrete'[1] is not approved under EU building codes (C10).

Time, money and knowledge mitigate against the use of new environmentally-friendly materials (A2, A9, A12). Education is lacking: "I think most architects have no clue…what is the [emissions] impact of the decisions that they make" (A14). Architects may specify materials in detail, or they may specify the qualities of the different materials and contractors are left to make the final selection, or they may simply design the 'look and feel' of a building – norms vary between countries (C1, C5, C9). Clients have the ultimate choice and focus more on cost than environmental impact (A16, C1). Architects have to persuade clients to use new materials, then constructors, lacking familiarity with the new material, will try to dissuade the client from doing so. Only two firms interviewed, both Dutch, used BIM to actively design using alternative materials to lower the whole life carbon of their buildings. One was a vertically integrated constructor currently building to a level 30%-60% lower than the Dutch lifecycle emission standard, MPG (C6); see Table 2.

Offsite construction, enabled by BIM, is an alternative strategy to material substitution for reducing embodied emissions – up to 66% savings against benchmarks [89,90]. Lighter, less carbon-intensive offsite fabricated office or apartment modules in turn need lighter concrete structures and foundations to support the modules on site (A14). In combination these techniques should yield substantial material savings but durability is unproven [91]. Modularisation can amplify the environmental benefits of prefabrication but its use currently for sections of rooms (rather than whole units) is driven by constructors' desire for speed, not by achievable material or emissions savings (C10).

One clear driver of BIM adoption linked to environmental performance is green certification. Commercial buildings are increasingly built with green certifications, which include compliance with standards including BREEAM (UK), LEED (US) or DGNB (Germany). All these are widely used in Europe. Green certification incurs higher costs, and BIM is necessary to complete the data requirements for many of these standards. For example, DGNB requires an LCA calculation, for BREEAM an LCA is useful, while LEED does not require one [92]. Certifications add value though two mechanisms. Firstly, lower operational energy requirements reduce occupant outgoings so space can be rented for more money (L1, L9). Secondly, in oversupplied markets they provide comfort against obsolescence for property investors and for banks (*L*11), so loan finance may be cheaper (L9, *L*10). It is unclear (to developers or banks) whether lower embodied emissions leads to a higher building value, as operational energy is independent of this (L9, *L*11). Potentially, new low emission materials would assist qualification for green certifications, but until these become recognised by the certifying bodies they will not be used (C2). Hence the need for regulation, without which there is no incentive to reduce embodied emissions levels (L9, *L*11).

4.7. PESTLE synthesis

Overall, applying the PESTLE framework to our interview data, we visualise our findings under each of the six dimensions in Fig. 2, distinguishing BIM adoption drivers (green) and barriers (red). These are further summarised as follows:

Political. Regulatory and legislative drivers of BIM adoption have been weak outside pioneer countries with existing mandated limits to building lifecycle emissions. However, the policy landscape is changing, with more widespread regulatory incentives set to diffuse across EU countries.

Economic. Economic costs with BIM use are more direct and salient to firms compared with the efficiency and time-saving benefits, particularly among smaller architect and constructor firms for whom skills' shortages compound barriers to BIM adoption. The economic value of BIM is clearer in larger, complex, multi-actor projects or in vertically integrated firms.

Social. An important barrier to the use of complex BIM tools are technical skills upgrades and training needs for personnel. BIM upskilling in turn changes roles and relationships within firms as part of wider cultural change necessary for embedding BIM in firms' practices. The exchange of BIM between different actors along buildings' value chains, particularly between constructors and facility managers, is further complicated by varying technical capabilities and interoperability issues.

Technical. Enablers of BIM adoption include easy data handling and in-house tool development. Barriers include outdated software and the non-substitutability of professional expertise and judgement for key decisions. BIM's usefulness to firms is derived from the tools and applications built off its data resources, and these are many and varied such that there is no standardised technical use case for BIM among practitioners.

Legal. Liability and insurance issues with BIM applications constrain its use for designing with novel building materials or reusing building components. This affects the potential for BIM to integrate lighter weight, bio-based, or otherwise more materially-efficient elements into buildings. Even though monitoring compliance with building codes and standards could be another use case for BIM, this is currently not needed as 2D drawings still largely suffice.

Environmental. BIM is useful for demonstrating compliance with performance standards and green certifications that can command a price premium in commercial building markets. The wider potential for BIM to stimulate the use of lighter, lower carbon, or otherwise more

[1] Low emission cement is an umbrella term for cements not using the same chemical reaction as Ordinary Portland Cement in their binders: they need approval on a case-by-case basis for specific applications.

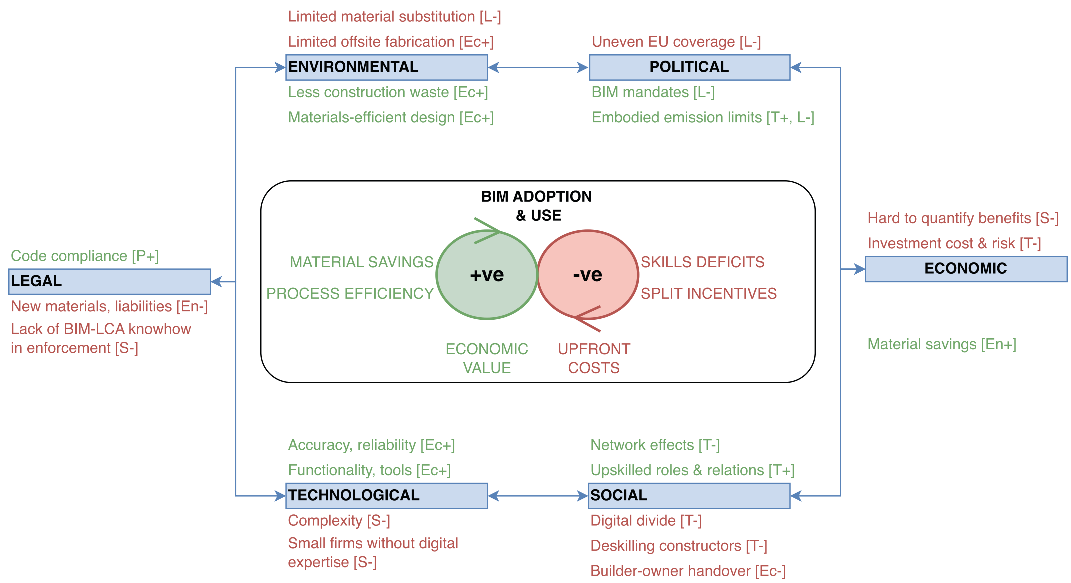

Fig. 2. Main drivers and barriers of BIM adoption and use along the six dimensions of the PESTLE framework. Key: +ve = positive feedback loop; −ve = negative feedback loop; green = BIM adoption drivers; red = BIM adoption barriers; [ ] = link to other PESTLE dimension, e.g. [S-] = link to adoption barrier under Social, e.g. [En+] = link to adoption driver under Environmental. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

sustainable building materials (including wood) and building components is still largely unrealised due to a lack of strong incentives and inertia to change among firms.

5. Discussion

Our expert interviews build on the literature reviewed by providing a rich practitioner perspective on the current state of BIM adoption and use, and how the drivers and barriers vary across both firm type and size, and by country. In this discussion, we return to our research questions and set out the new insights from our integrated PESTLE analysis.

RQ1. What are the drivers and barriers of BIM adoption among firms for building design and construction?

BIM still has a relatively low adoption rate. BIM suffers from low penetration amongst smaller architects and in small and medium sized contractors, and more so for any moderately advanced functions such as clash detection and Bills of Materials, with a 5% usage level even amongst BIM adopters [71]. Penetration rises to about 32% of users in larger firms [93].

BIM's economic value proposition remains unclear. There remains considerable confusion within industry over what BIM actually is [94]. This makes it difficult to identify and quantify time, process, and material savings [26]. BIM should lead to a more accurate and overall lower price tender than CAD [50]. This helps clients and constructors, but the savings to architects investing time in the initial BIM are more intangible [26]. Only one interviewee – a constructor – was able to estimate savings figures in any area. All interviewees from vertically integrated firms (design and construction) who did not face this split incentive issue between design and construction were committed to BIM. Increased BIM penetration is unlikely without more tangible, visible business needs or benefits. BIM produces better accuracy and control – continued into construction, it delivers shorter build times, which is the primary financial incentive for constructors for BIM use. However, one interviewee who supplied automation software to the construction industry remarked that she had rarely seen a BIM model that was updated throughout construction. Without any checks on the final model, quality implementations of BIM that contribute to control and savings are less likely. Better tools now being marketed, such as automated integration of BIM with site video recordings to enable precise progress chasing, suggest that incentives for larger constructors to install BIM are growing.

BIM use requires upskilling to overcome digital divides within and between firms. With few exceptions, university and colleges do not teach students the principles or use of BIM. This is a major opportunity for improvement which would aid adoption, reduce business training costs, and reduce the digital divides found across architects and construction firms. Firms need a BIM education to see its value [38]. Much of the current training is carried out in-house, hindering the growth of BIM into smaller firms. External training carries a cost: smaller firms, struggling to see payback from BIM, are well aware that the costs of implementation greatly exceed the software licence cost [35]. Additionally, the more obvious payback items such as clash detection, Bills of Materials production and modification of existing designs to fulfil new commissions need significant competency in the set-up and structured use of the BIM.

Continuing digital innovation is opening up new use cases for BIM. AI can generate designs for sections of buildings, subject to a set of energy constraints [95] or simplify structural design [96]. Digital twins in conjunction with the Internet of Things offer potential for real-time monitoring and control [97], though these would be constructed from a BIM extract, as BIM is not capable of real-time multiple sensor input–output or use with digital twin tools [34]. These novel BIM applications are still in their infancy but could contribute significantly in future. Alongside this, the rapid creation of EPDs by manufacturers and software are enabling easier calculation of buildings' whole life carbon emissions [14]. Coupling BIM with buildings' material passports and LCA can inform material use and reuse decisions from design to end-of-life [14]. Technical issues with the use of BIM-LCA tools are being rapidly overcome, and LCA provides a means of ensuring that expected 'design efficiencies' incorporated in third parties' modelled projections are realised.

RQ2. What contribution can BIM make to reducing whole life carbon emissions from buildings if it becomes widely adopted?

BIM can enable material savings but this is more technical potential than reality at present. BIM enables material savings in design (avoidance of over-specification), in early clash detection [46], in build accuracy (less rework as mistakes spotted earlier), in reduced on-site waste through more accurate Bills of Materials, in modular construction [15], and in maintenance of the completed building [26]. Although BIM users and clients can speak to these benefits of BIM in general terms, they are rarely quantified [94]. Of these potential material savings, clash detection and build modularisation are BIM-specific and are unlikely to be achieved through CAD. Few interviewees clearly saw the usefulness of BIM in terms of materials or energy savings; rather, BIM was understood through its fit to internal business practices. Apart from in specialist consultancies and for green certified construction of commercial buildings, BIM is not being used to design for material and energy savings beyond current legal requirements.

Regulated limits to buildings' lifecycle emission will drive BIM adoption. As BIM or CAD is essential to calculate embodied and projected operational emissions under whole life carbon legislation[5], this should provide the impetus to: (i) use BIM for material and energy efficiencies among firms already using a high degree of BIM's functionality; (ii) incentivise the 95% of smaller firms not using more advanced BIM capabilities to do so; (iii) induce firms which have not yet adopted BIM to try it. As legal emission limits on buildings will be tightened over time, BIM and CAD are the only available tools to recalculate the impacts of changing design and materials. However, progress to full implementation relies on several factors. First, governments across Europe must set legal limits and then reduce them till an impact is felt, at which point resistance is likely from industry. This dictates a widespread increase in the use of 3D CAD or BIM across construction, implying major cultural change and upskilling amongst smaller constructors even in countries regarded as more digitally advanced, and yet more culturally difficult in countries with little practice in data sharing between architects and constructors. Second, municipalities have to skill up to understand the LCA calculations and be competent to query them, otherwise unaudited 'self-declarations' may cause the regulations to lose credibility. Third, building codes must adapt to allow new materials to be used, which will be resisted by vested interests based on perceived risks and costs of change. A balance will need to be drawn between safety, pragmatism and risk, especially if new materials do not have proven lifespans or are reused and for which there are warranty or insurance issues.

BIM design functionality enables greater use of low-emission materials including wood. BIM tools can facilitate replacement of (for example) concrete beams with cross-laminated timber, or concrete partitions with bio-based alternatives. However the attitude of the BIM software user is more fundamental to the environmental outcome than the BIM itself. There is still very limited evidence that BIM is affecting the selection of materials, outside the four countries with embodied emissions legislation and specialist architects firms building to green certification standards.

Lifecycle emission reductions of 21–31% are realistically achievable 10 years since policy inception. We quantify projected savings from whole life carbon legislation based on the published targets in the four pioneer Northern European countries with existing regulatory limits (Table 2). We estimate that after 10 years from a policy decision, including a 3-year familiarisation period before limit imposition, embodied emissions in new buildings could be reduced by 21–31% with further gains possible if targets are tightened (Fig. 3). This assumes no building types are exempted from the limits. (We provide full details of our projection method and assumptions in Appendix A4).

Other European countries may not be as ambitious with their target emission reductions as the four pioneer countries. However, positive signs are evidenced by a Dutch interviewee already delivering to the Dutch standard less 30%-60% depending on building type (C6) and a Danish interviewee arguing 6kgCO_2/m^2/yr is achievable against an initial target of 12kgCO_2/m^2/yr (L2). Published national aims are also ambitious, for example Sweden is aiming for an 80% saving by 2043 [98].

There is overlap between embodied emission reductions driven by legislation and reductions from projected design efficiencies (particularly in cement and steel), such as those estimated at 20% to 2050 by the UK Green Building Council [99]. However the EU's whole life carbon legislation [5] is a key for unlocking these savings in practice.

6. Conclusions

Our study of expert practitioners' experiences with, and perceptions of, BIM found a settled pattern of limited adoption, with a marked digital divide between high-tech (BIM and tools) and lower tech (3D CAD) architects. Constructors predominantly worked from 2D plans without BIM, though some larger firms had higher level of BIM adoption. We found significant barriers to more widespread adoption across the dimensions of the PESTLE framework. These barriers include current practices, work cultures, regulations, and skills needs for digital systems, particularly in construction.

We also investigated whether further use of BIM across the architecture, engineering and construction (AEC) sector is changing materials use and efficiencies, with a beneficial impact on embodied emissions through material selection, using less material and extending the life of

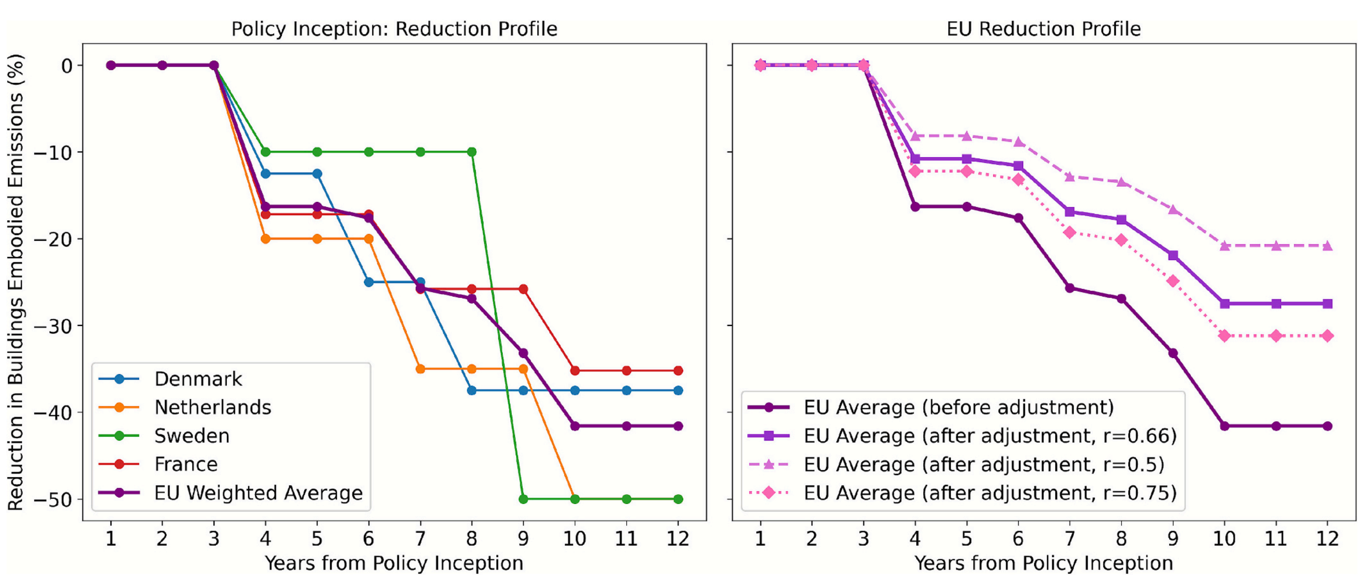

Fig. 3. Potential impact of embodied emissions legislation in four pioneer countries (left panel) extrapolated to EU average (left panel central estimate, and right panel for range). Note EU averages based on adjustment factor, r, as estimate of legislated limit achievable in practice. (See Appendix A4 for details).

building components. We found the use of BIM for material savings depends largely on the motives of the users to incorporate new lower-emission materials, and on the sophistication of the model and its ability to act as a tool for delivering control, implying better specification of bills of materials, improved clash detection and less rework. To-date, this drive towards lower emission materials has been limited to a medium-sized environmentally-oriented firms. However, governments across the EU now have to formulate and implement whole life carbon limits for buildings from 2028 to 2030 in line with the EPBD [5], following the precedent of pioneer Nordic countries and France. This will force design and practice changes by architects and constructors, together with rapid approval of new and reused materials to enable embodied energy reductions. BIM will be a critical enabler but not a panacea. We found that public authorities have limited capacity to understand BIM-LCA calculations, monitor and enforce embodied emission limits. At best this risks reducing the effectiveness of the legislation and at worst will bring it into disrepute as a control mechanism. Whole life carbon regulations in countries with limited digitalisation in construction is a long-term process involving education and changes in practice. The digital skills base in constructors across Europe is very low and needs rapid improvement to meet the goals of the new regulations.

The major challenge for BIM use depends on how compliance to the EPBD can be achieved across the EU by 2030 as planned, while minimising disruption and cultural resistance from constructors and obtaining understanding and control of construction data by local authorities, against a background of low preparedness levels. This is a key question for further research.

Finally, we note specific limitations to our study. First, the number of interviewees, spread across the whole of Europe, necessarily limits generalisability of results. Second, despite attempts to contact architects and constructors uniformly across Europe, northern states are over-represented as are firms which did not use BIM: these interviews were harder to obtain. However, our two main conclusions – that firms are not designing or building for material and embodied energy savings, and that EPDB 2024 could significantly impact BIM uptake as an enabler of lifecycle emission reductions are robust to these sample characteristics, given that states with lower penetration of BIM (under-represented in the sample) have fewer advanced users.

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CRediT authorship contribution statement

Martin Burgess: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Charlie Wilson:** Writing – review & editing, Visualization, Supervision, Funding acquisition, Conceptualization. **Yee Van Fan:** Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2026.116953.

Data availability

Data will be made available on request.

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