Does Digitalisation of Building Design and Construction enable real-world material and energy savings in Europe?

A Circular Economy study of Building Information Modelling (BIM) use.

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Disclaimer

Statement of originality

This deliverable contains original unpublished work except where clearly indicated otherwise. Acknowledgement of previously published material and of the work of others has been made through appropriate citation, quotation or both.

This report is based on 41 interviews across Europe. The original intention of this document is to inform those individuals and organisations kind enough to assist in the interviews of the knowledge and opinions of their colleagues. It has now been made open to a wider circulation. Any errors are the author's alone.

It does not follow that these thoughts are necessarily an accurate reflection of the general body of opinion in those European states represented, but does paint a broad picture of variation across Europe.

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Executive Summary

Buildings and construction (construction, heating, lighting, cooling) account for about 41% of European greenhouse gas (GHG) emissions[1] and major reductions are necessary to fight climate change. This study investigated the impact of digitalisation of design and construction on the reduction of emissions and advancement of the Circular Economy (CE) (Box 1 outlines the Circular Economy concept).

Building Information Modelling (BIM) has long been promoted by the EU and certain member states: it theoretically contains data facilitating energy-efficient design and construction. Interviews with 41 architects, consultants and constructors across 11 European countries showed that BIM is little used by smaller architects and constructors, in line with previous research. Larger firms use BIM as a design and data processing tool to enable collaboration between project partners. Most digital tool innovation is to speed construction: current evidence of BIM-enabled calculations impacting material usage, or embodied emissions, or lifetime emissions through the design process is minimal and limited to environmental specialists.

Interviews revealed that the main drivers of GHG emissions reduction in the commercial buildings sector are institutional investors and regulations. This is both statutory for thermal efficiency, but also through 'Green Certification' standards. The compliance process requires BIM; certification increases the building's value to end investors by adding perceived protection against obsolescence. In addition, there are a small number of environmentally conscious architect's firms which influence design and materials within their remits.

Hitherto regulations have governed only operational emissions; targets have been achieved by use of specific materials chosen to produce the required heat loss levels and have not normally necessitated use of complex digitalisation. This is changing: Denmark, France, Sweden and the Netherlands have introduced whole-of-life CO_2e emission calculations into law, covering both embodied and operational emissions, with maximum limits per m^2 of floor area. Calculations all require design digitalisation: most standards also require digital modelling of completed construction. Interviews show that design changes are not yet forced, but if current political intentions are fulfilled, reducing limits will impact on design, materials and embodied emissions within 5 years across all new buildings: already industry attitudes towards reducing embodied emissions have transformed in these countries. Significant changes in materials and construction practices will be required, likely involving building code updates and almost certainly requiring training of constructors and municiplaities in digital systems. The EU has mandated similar regulations EU-wide for all new buildings from 2030. If implemented with the same ambition as the 4 pilot states, savings could be 21%-31% of embodied emissions after 10 years. Digitalisation will then be enabling wide-scale material and energy savings.

These Life-Cycle Analysis (LCA) regulations indicate a second wave of digitalisation in architects, and a first wave in most contractors. Currently, interviews suggest architects work in settled niches: in general, smaller firms use 3D CAD from which they produce 2D plans for contractors, and larger firms working on larger commercial or public projects use BIM, which may be used by the contractors or may not. Constructors at the small and medium sized level do not generally use digital systems or tools. Requirements for as-built models to enable LCAs to be calculated at build completion appear to necessitate smaller constructors digitalising for the first time. Secondly, LCA calculations are generated more easily through BIM than CAD, which may spur upgrading to BIM. Legislators perceive use of BIM in design and construction will assist designers to lower embodied emissions very significantly: for example, the Swedish target 80% reductions by 2043[2].

While interviewees in the four impacted states were wholly in favour of the legislation, political support has to exist for emission limits to reduce and technical difficulties surpassed. At this early stage, the positive revision of ideas noted in the results is supported by the rapid creation of embodied emission figures by building product manufacturers and software to enable easier calculation of the LCA, which suggests that technical issues with performance of the calculation will be rapidly overcome. Furthermore, LCA offers a method of ensuring that expected ‘design efficiencies’ incorporated in third parties modelled projections are realised. Governments now have to follow through and implement limits which will force design and practice changes by architects and constructors respectively. Interviewees suggest the authorities have a current inability to understand, monitor or enforce correct calculations, which if continued will at best reduce the effectiveness of the legislation and at worst bring it into disrepute as a control mechanism. Cultural norms in some states whereby constructors expect to profit from rework and design errors will be less possible on building sites under digital control: resistance to implementation is likely and will have to be overcome for a successful outcome.

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 (FM) software. This commonly leads to a break point in the data trail when the building is completed, with apparent loss of much of the building information which could otherwise have greatly assisted planned maintenance programs and reduction of replacement parts, clearly a CE aim. 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.

The Circular Economy (CE), Net Zero (NZ) and Digitalisation

The concept of the Circular Economy (CE) is that by minimising energy and material consumption in the production, use and reuse of materials, great moves towards sustainability can be made. CE measures to reduce material quantities in new projects, or to prolong lives of materials by retrofitting, refurbishing, repurposing or deconstructing and reusing the infrastructure at the end of its first life could contribute significantly to GHG reductions over the medium term.

When allied to digitalisation (for example in building design or the production of advanced cutting plans), efficient use, reuse or recycling of materials is potentially enhanced and GHG savings made. Digitalisation of life is growing rapidly in most spheres: the project investigated the use of digitalisation in design and construction to further the ends of the CE.

Digitalisation of the Architecture, Engineering and Construction industry (AEC) has resulted in nearly all European buildings being designed on CAD and/or BIM. Digitalisation provides clarity, speed and flexibility to architects and 2D plans/3D visualisations for constructors. For constructors using BIM it can also assist with build accuracy, job scheduling and progress chasing to improve speed of delivery and reduce costs. However, the study revealed that in general digital systems have not been used with the intention of reducing material usage or advancement of the CE.

Net Zero goals can be furthered by reducing operational emissions during the life of the building, whether in heating, cooling or lighting, and also by maintaining the building more efficiently to avoid unnecessary replacement of fittings. The CE also benefits from reduced embodied emissions (those emissions generated during the extraction or fabrication of the materials in the building, which can be up to 74% of the whole-of-life emissions from a new building with advanced energy performance[1]). Embodied emissions have increased importance as they affect the climate now rather than at a time in the future. Lastly, the CE benefits from reduced material wastage through better design, clash detection, avoidance of error and rework, use of modular construction and reuse of parts or materials. All can be assisted by digitalisation.

In strict academic terms saving of materials is an aim of the CE and saving of energy is an aim of Net Zero. For ease of reading no distinction is made in this report.

Box 1: A brief outline of the Circular Economy

1. Purpose of study

The project started with a utopian ideal that, in a perfect world, digitalisation could be used to design a building and then that initial design could be modified through an iterative process to achieve an acceptable balance between cost and the total of embodied and operational emissions, thereby furthering the aims of the Circular Economy and sustainability. The study then "worked backwards" to discover the reality of practice and obstacles preventing this ideal.

It is part of the wider Horizon 2020 'CircEUlar' project for the European Commission, projecting the likely emissions from buildings and mobility through to 2050. The theme of rampant growth in digitalisation cuts across both these sectors, in particular with the view that it should be contributing to sustainability, not to the linear ('use it and throw it') economy.

As thermal efficiency of new buildings has improved embodied emissions have become more important as a proportion of lifetime total emissions. Figure 1 shows an illustration of the current relationship between embodied and operational emissions for conventionally constructed buildings in the UK, when it takes at least 30 years of operational emissions to match the emissions made at the time the building was constructed. Given the speed with which total emissions have to be reduced and the immediacy of embodied emissions, curtailing embodied emissions is very much in the focus of legislators.

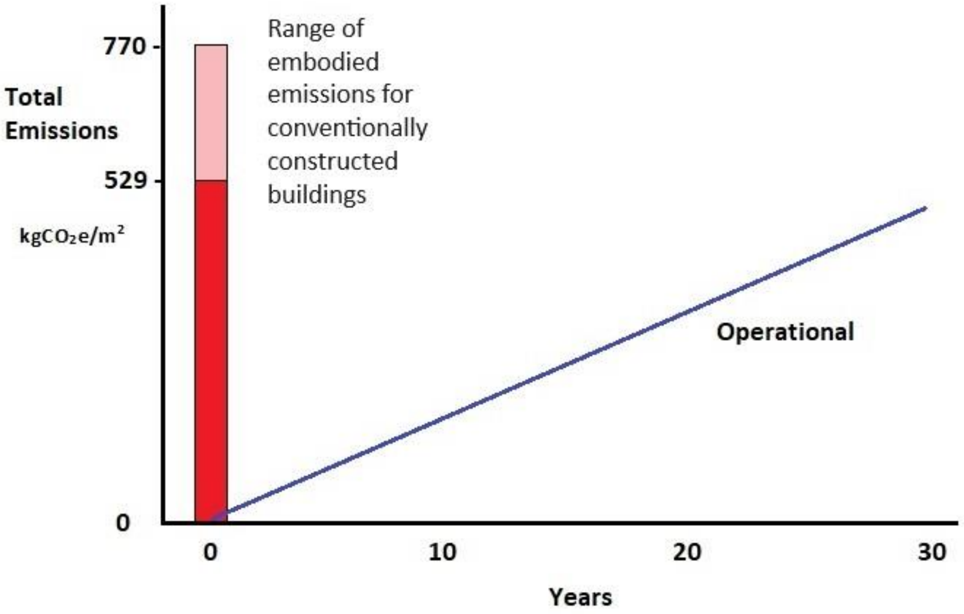

Figure 1:
Illustrative Embodied & Operational emissions from new commercial buildings in the UK

Sources: Embodied carbon range[3]
Operational emissions[4], carbon intensity of UK electricity[5]. Embodied emissions will vary across Europe dependent on materials and climate, as will carbon intensity of grid supply.

2. Structure of the report

During the study an interviewee remarked that architects and constructors were both in the same sector but remained very siloed: there is little crossover (Interviewee C10). It is possible to present this report in sections dealing with the two silos separately, but as so many of the findings relate to both they are largely presented side by side in the text.

The study is about the impact of digitalisation on the CE, which in AEC is reflected primarily as economies of energy (operational and embodied) with embodied energy being saved through better use of materials (use less; use materials with lower embodied energy; reuse). The situation as discovered during the study is reported in two results sections. The first deals with the factors tending to preserve the existing position in respect of the CE. Part 2 covers changes in practice and legislation which further the aims of the CE.

An Introduction and brief note on methodology is followed by Part 1 of the Results, dealing with the use of BIM and 3D CAD, then by generic industry issues such as emerging digital divides, collaboration with others and the use of BIM for Facilities Management. Part 2 of the Results then covers Green Certifications, Life Cycle Analysis (LCA) legislation and use of new materials.

3. Introduction

This study examines the potential for digitalisation (primarily Buildings Information Modelling - BIM) to contribute GHG emissions savings from buildings in Europe (the EU plus UK and Norway). It appears that few studies have interviewed industry participants and attempted to clarify whether, how and who uses BIM in practice or whether it makes sense for AEC firms to adopt BIM (as noted in[6, 7]). Many academic papers believe adoption of BIM is logical (aligning with the EU narrative), so failure to adopt is simply down to lack of information, education and process understanding, perceived to be common in smaller firms[8]. This research attempts to address this gap.

It is known that efficient use of BIM implies architects sharing model data with contractors: existing work suggests that the short-term project-by-project culture in the AEC industry and an unwillingness to share information for perceived competitive reasons[9] mitigates against collaborative practices necessary[10].

'Embodied emissions' refers to emissions created in the extraction and fabrication of components and to emissions created in the construction process. Material selection, component reuse and prefabrication are key to achieve embodied energy efficiency[11-13], which are largely independent of BIM use. Many savings are determined at the design stage[14, 15]. There are relatively few papers focussing on BIM's use in the CE[11]. Those that do exist focus on BIM as an essential prerequisite following which cost, material efficiency and energy savings will flow[11, 16]. There is limited literary coverage of the link between BIM and the CE in practice.

The CE also embraces planned maintenance to reduce parts replacement during a buildings life: there are few papers on BIMs role in this, or on its use to manage energy systems. Unsurprisingly, architects and owners roles appear to prioritise immediate transactional value and not the CE[15]. With lifetime refurbishment costs commonly totalling over half the building cost this is not ideal[17]. At end-of-life, BIMs relative newness means most buildings needing refurbishment do not have a BIM, and tendering processes mitigate against costly BIM creation[17].

Minimising the combined total of embodied and operational emissions implies producing a Life Cycle Analysis (LCA) of a construction design. Embodied emissions data for each of the myriad of elements is held in individual Environmental Product Declarations (EPDs). Using BIM for LCAs requires automated data exchanges with an EPD database: though data interchange is recognised as a BIM weakness[18]. Data output and input is generally through a commonly agreed system known as IFC ("Industrial Foundation Classes") which contains a selection of the model data.

3.1 Political background: BIM

Digitalisation of building design, construction and management can potentially contribute significantly to the CE[11, 19]. EU policy supports digitalisation through BIM to (i) provide data on buildings[20], (ii) achieve embodied emissions savings and further the CE[19], and (iii) aid cost savings[13].

Political support historically came in two forms: firstly, state agencies in individual northern European countries making BIM mandatory for public contracts, and secondarily in support of developing standards governing its use. This promotion by government bodies appears to have been crucial in achieving the acknowledged leadership of the UK and Nordic countries[21]. Figure 2 shows a European map shaded according to the level of mandation of BIM for national government work: in this study it is used to stratify European architects into groups for sampling.

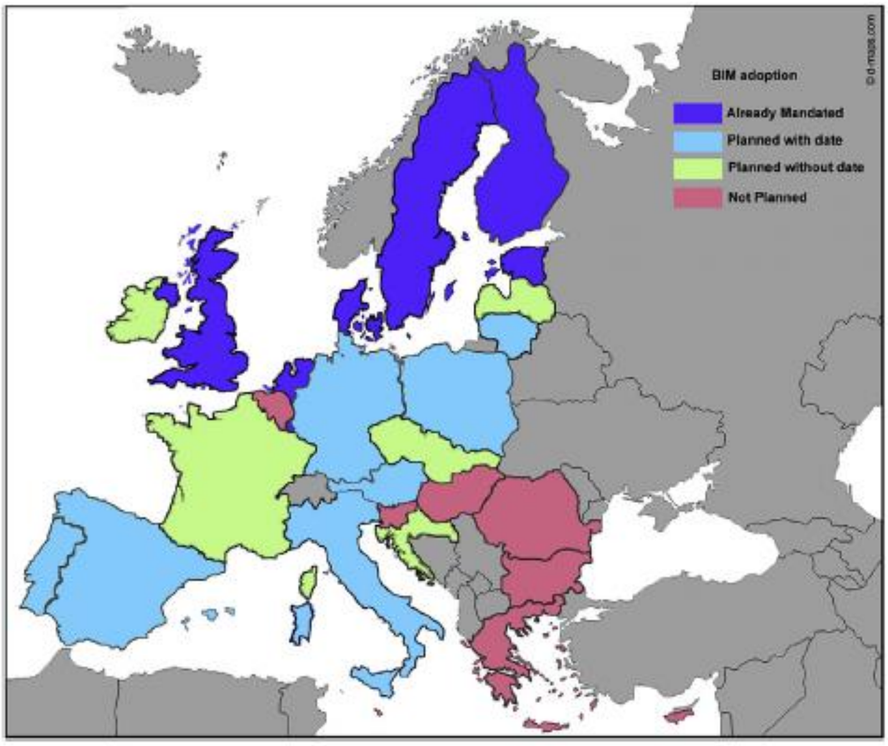

Figure 2: State of mandation of BIM for government work across Europe, May 2017.
Source: Charef et al (2019) [21]

3.2 Political and Regulatory background to digitalisation and energy efficiency

Until recently the focus of legislation in EU member states was optimising design to improve operational energy efficiency[20], leading to a 32% drop in operational emissions since 1990 but only 6% fewer embodied emissions[22]. The EU Commission explicitly supports BIM as a method of achieving cost savings, suggesting 13%-21% from design and construction and 10%-17% in operations[13, 23].

In a voluntary survey by the Association of European Architects only 31% of European architects firms used BIM in 2020[24], and 62% used 3D CAD (ibid), though the representativeness of responders across age group and firm size is unclear. Notably, European regulations on operational energy usage stipulate maximum levels of heat losses per square metre through walls, floors and ceilings. Typically, architects and constructors know that if they select materials with specific properties these levels will be achieved: design digitalisation is unnecessary to meet thermal loss regulations.

In the last five years legislation limiting embodied emissions in buildings has been passed in four states and well before 2030 these limits will have legal force: buildings exceeding the limit will be denied occupation permits, creating incentives to design and construct to reduce embodied emissions. These states are Denmark (termed BR18), France (RE2020), Sweden (Swedish Climate Declarations) and Netherlands (MPG) (Table 1 provides the main details). All differ in methodology, coverage and exemptions.

Norway, Finland, Belgium and Iceland are developing similar regulations[25], and they already exist in Toronto and California (A14). London planning regulations (covering 9 million people) include a requirement for an LCA in larger developments: the figure can be taken into account when approving a planning application, but there is no legal limit in the UK[26]. UK central government projects require an as-built BIM to be produced (C3,[27]).

More recently, the revised Energy Performance of Buildings Directive mandates EU states to include measures of embodied carbon in building permitting by May 2026, and by 1 January 2027 set legal limits for total life-cycle carbon from 1 January 2030 for all buildings, including domestic (and for buildings over 1000m^2 by 1 Jan 2028)[19], such limits to have a progressive downward trend. This is a rapid program of change. The systems required are not detailed: LCA production from 3D CAD is possible, though easier from BIM as it holds more data on each element, so these rules will likely boost adoption of BIM. The EPBD does not detail whether the calculation is performed at planning or completion, or both.

State / Policy name	Key Dates	Calculation notes	Exemptions
France RE2020	From 1 Jan 2022 for residential & office buildings, 2023 for all buildings. Limits tightened in 2025, 2028 and 2031.	Entire life cycle. 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.
Denmark BR18	LCA submissions necessary from 2023 for all buildings. No limits apply for buildings <1000m^2 until 2025	Limit: 12 kg CO_2e/m^2/year for all buildings > 1000m^2. Over 50 year life. Modules A1-A3[5]. Single assessment at completion. Plans to lower the limit every 2 years.	Buildings <1000m^2 until 2025. Renovations. Plumbing and electrical works.
Sweden Swedish Climate Declaration	Submissions necessary against building permits issued from 1 Jan 2022 Legal limits enforced from 1 July 2025	kg CO_2e /m^2 gross floor area Modules A1-A5[1] Plans to lower limit in 2030, 2035 and 2043. 25% reduction proposed in 2030. Single assessment at completion.	Most buildings until 2027: Regs apply principally to new offices and apartment blocks > 100m^2. Excludes operational emissions until 2027, when it becomes a full LCA for almost all buildings. 50 year life assumed.
Netherlands MPG	From 1 Jan 2018. Limit of €1.0/m^2/year, reduced to €0.8/m^2/year for residential buildings from 1 July 2021.	Covers fabric of new building plus any component replacements. 50 year life. Includes measures other than CO_2e, such as material toxicity and ozone layer depletion. Damage valued at the social cost of carbon and result expressed in €/m^2/year. Single assessment at planning.	All exempt except new offices and residential. Excludes operational emissions, which are covered separately under the BENG regulations.
European Union Revised Energy Performance of Buildings Directive (2024)	From 1/1/2027 From 1/1/28 From 1/1/30	Each state to publish plan for LCA calculations and reducing limits on all new buildings. LCA mandated - new buildings LCA mandated - new buildings	Buildings > 1000 m^2 All new buildings

Table 1. Key details of current embodied emissions regulations in EU member states.

References: Sweden[28] [25] [29]; Denmark[30]; France[31]; Netherland [32]. The Dutch MPG system involves weighting the different elements, which is subjective: straight CO_2 measures are cleaner (A14, C5).

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[1] A1 Raw Material Supply; A2 Transport; A3 Manufacturing; A4 Transport; A5 Construction & Installation processes.

3.3 Economic background

Statistically, 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[24]. The relatively low BIM adoption rate of 31% (ibid) suggests that architects (or their clients) do not readily see its benefits. Creating a BIM is costly: any savings accruing to the clients during design and construction are unlikely to benefit the architects directly[6]. Architects may adopt BIM if they foresee cost savings in their own practices, but literature suggests that BIM is not perceived to save office time or money[17].

The major economic benefits of BIM are promoted as collaboration, document management, time saving in a multi-user environment, virtual reality to assist design, and the ability to use mobile devices on site[33]. Autodesk Revit is the market leading software[34]. Notably, these benefits apply far more to large firm, multi-actor, multi-firm jobs than a single architect-contractor relationship. Actors write their own BIM tools in response to perceptions of need or customer demand, presumably to gain a competitive edge[35], but realistically this is again the reserve of larger companies. The socio-structural differences between the smallest and largest firms, together with types and complexity of work done, appear to be a key determinant of practices

3.4 Technological background

There are numerous BIM platforms such as ArchiCad, Autodesk Revit, Infurnia, Navisworks, Tekla and Trimble. Multiple applications ('tools') can run against model data, many incorporating third party data which are self-created or purchased, such as tools to calculate points for green certification schemes[36]. A list of examples of tools is given in Appendix 2. Data standards have been established to enable interoperability between BIM and tools, with data losses consistently cited as a significant issue[14, 37].

4. Methodology

Geographically, the study covered the EU 27 plus UK and Norway, referred to collectively as 'Europe'. The premise of the study – the possibility of optimising embodied and operational emissions subject to constraints (most obviously cost) – focused immediate attention on the use, or not, of Business Information Modelling (BIM). Initial reading covered academic papers, trade journals and BIM textbooks. The bulk of research effort was directed towards interviewing, and some 41 interviews, email exchanges and short conversations with architects and construction managers were carried out across 11 European countries. The great majority were between 30 minutes and an hour, were recorded, transcribed, themes identified and then consolidated and digested. Two of the exchanges were by email, and the interviews with architects firms who had limited use for BIM tended to be shorter.

The sample of architects for interview was selected randomly from national databases of qualified architects. A second sample of architects was taken by similar methods in Denmark and Sweden to study the impact of the recent LCA legislation. For constructors, no equivalent databases exist, and penetration of digitalised systems is far lower than for architects, making random methods unsuitable. Constructors were contacted primarily through contacts made at trade shows and by recommendations from previous interviewees.

As in all interview studies, responders bias in favour of those interested in talking about the subject, so the work will inevitably feature responses from firms more digitalised than the average. Also, northern Europeans responded more frequently: not only are they more digitalised, but they are also likely to have larger proportion of English speakers.

In total, 114 firms were emailed and followed up, leading to 41 interviews: responders were primarily from the Netherlands and the Nordics. Architects interviews are referenced A1-A18, constructors C1-C11 and LCA interviews LCA1-LCA12.

Table 2: Final list of interviewees.

Country group	**Small:** **1-2 architect**	**Medium:** **3-9 architect**	**Large:** **>10 architect**
A: BIM already mandated by government	A1 (UK) A2 (Netherlands) A3 (Norway) A4 (Sweden, 5 min) A5 (UK, 5 min) A6 (UK, 5 min)	A8 (Netherlands) A9 (Netherlands) A10 (Norway, 5min) A11 (Netherlands, emails) A12 (Netherlands)	A14 (Netherlands)
B: Mandation planned with implementation date			
C: Mandation planned without implementation date	A7 (Croatia)	A13 (Ireland, email)	A15 (Latvia) A16 (Latvia)
D: No government mandation plans		A18 (Slovenia)	A17 (Belgium)
Actual Target	7 8	7 7	4 3

Constructors	C1 (UK)	Medium sized builders £10k-£1m+ jobs
	C2 (UK)	International consultancy partner
	C3 (UK)	Head of Sustainability, large UK housebuilder
	C4 (UK)	CPO, Building Data Automation company
	C5 (Netherlands)	Large real estate developer
	C6 (Netherlands)	85 yo family builder, industrial, office & home
	C7 (France)	6yo, 4 person BIM consultancy
	C8 (Spain)	UK based Tier 1 Constructor
	C9 (Belgium)	Start-up BIM software firm
	C10 (France)	Multinational constructor
	C11 (Greece)	UK based multinational constructor
LCA Legislation (architects and valuers)	LCA1 (Denmark)	Large firm
	LCA2 (Denmark)	Danish Architects Association
	LCA3 (Denmark)	Large firm
	LCA4 (Denmark)	Large firm
	LCA5 (Denmark)	Large firm
	LCA6 (Sweden)	Large projects, small firm
	LCA7 (Sweden)	Small firm
	LCA8 (Sweden)	Medium Firm
	LCA9 (Sweden)	Large residential & light industrial financier & developer
	LCA10 (International)	Climate Bonds specialist
	LCA11 (UK)	UK based property valuer
	LCA12 (UK)	UK based property valuer

5. Results

Section A – Findings on the current situation, likely neutral in furthering the aims of the circular economy

5.1 3D CAD and BIM: Uses

The background is that 54% of European architects work is residential and over 50% refurbishments. For smaller architects firms (80% of European architects work in one or two architect firms) the historical benefits of BIM (such as the ability to collaborate with other firms) appear limited and *prima facie* do not use BIM[24]. For example, in Belgium an BIM-specialist interviewee estimated that 60-100 firms used BIM out of 90,000 construction businesses (C9), and a Spanish interviewee suggested BIM was only used in Spain for special projects such as the new Real Madrid stadium (C8).

Interviewees largely split between those dealing with contractors who used electronic systems and those who did not. Interviewees highlighted significant network effects (situations where benefits increase with more users, such as WhatsApp) in communication between BIM users, particularly in more exact data transfer (A11, A15): historical data interchange issues appear to have been largely solved. For non-users, there were no benefits from network effects (A2, A5, A7): their reality is that constructors like to see 3D visualisations of designs but rarely use anything more than 2D plans (A1, A7, A16). The use of 2D plans on site is ubiquitous, even in construction firms who use BIM (C2, C7, C10); only one firm displayed 2D plans on electronic devices and intended to remove the option for its construction workers to use paper in about 3 years. This interviewee was unaware of any other firms at the same stage of digitalisation (C6). Potential use of models on building sites requires simple interfaces and good data availability, needing small models that can be downloaded and updated easily, as site workers need the most up to date model in the right level of detail (C5).

The absence of network effects implies that BIM-using architects in a non-BIM environment have to amend models from returned 2D plans (A7). Without a network of users many architects do not persist with BIM (A1) and those that do may only get occasional request to supply data to a contractors BIM (A11, A13, A14).

Architects using 3D CAD use it for design and some use it to assist with Bill of Material production also. Architects using BIM may use it additionally to enable collaboration between individuals, both within and outside the firm (see 5.5), for production of compliance reporting (both building codes and green certifications (see 6.2), to enable control of the design process for complex projects and to enable specific design requests if clients demand them (for example, rotating the building design to enable best use of sunlight). No calculations are performed in BIM (A1, A2, A4, A14); these are carried out by other software (“tools”), operating on exported BIM data.

5.2 Design

The fundamental difference between 3D CAD and BIM is the amount of data that can be held against each element of the project. BIM set-up is an issue: 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); disciplined use is essential[34, 38] and internal company procedural manuals are key to control of the process (A15). This implies that it takes longer to set up a BIM model (A7), but that the data is potentially more useful in the tendering process, for clash detection and job scheduling. In reality, none of these save the architect money, and the client optics of paying an architect more to potentially save money later on are a barrier to implementation[39]. This is particularly an issue if the constructor does not use BIM. A situation where one party incurs costs which saves another party money is commonly known as a split incentive problem. If the firm is vertically integrated (it designs and constructs) there is no split incentive: perhaps a second reason (in addition to BIM solving communication problems in larger firms) why all the integrated firms interviewed used BIM.

Most BIM advocates thought using it made them better architects and designers (A7, A15, A16), and BIM design functionality has improved markedly in the last decade (C10). 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, A12, A13, A14, A16, A17) to provide immediate value metrics (such as square meterage or number of apartments) (A14). Linked Virtual Reality allows designers to 'walk around' inside the building and improve its design (A15, C5, C6) though it's also a sales aid (A16, C6) and can help individuals design their own homes (C5).

5.3 Economics

Beyond the initial cost of hardware and annual licences, the economics of BIM are not transparent. Few small firms either used it or would have used it had they had the opportunity. None of the smaller firms using BIM cited explicit cost savings as a reason for using it: users believe it aids productivity (A15, A16), work organisation and control of the project (A7), time optimisation and avoidance of mistakes (A18). It's a business enabling tool (A8) even if users have never tried to estimate productivity savings (A7, A11). Only one of the non-BIM users interviewed was planning to use it (A11; Netherlands): they expected increased costs in software and (initially) time, but this was offset by the strategic need to be able to tender for municipal work, for which BIM is a requirement in the Netherlands. He foresaw that not using it would lead to loss of business over time. Non-adopters cited difficulty of use: "It's a time thief" (A10), "Too fiddly" (A1), "Cumbersome" (A6), "Wastes time to learn" (A5), but in contrast a large-firm Estonian architect designed single houses using BIM when he worked in a 2-person firm, and did not believe arguments that it reduces profitability at that size level (A15). In particular, BIM produces Bills of Materials "very" accurately so this must lead to client savings (A16, large firm). However, clients demand a product: they do not demand BIM, and single houses can be hand drawn (A3).

The business model of one interviewees medium-sized firm was to sell single-home plans, using a pre-existing library of parameterised designs, quickly customised to the development site and the clients wishes (A9), believed to be similar to Huf Haus's customisation methodology (C1). This ability to cut time by constantly reusing designs (avoiding model set-up time) was not mentioned as a benefit by any other party. It does require a specific type of model set-up (C6).

For most contractors, the benefits of maintaining a BIM through construction to accurately reflect the final completion (an ‘as-built’ BIM) are unclear (A7, C2), unless the client requires it, as 3D visualisations and 2D plans to enable construction can be produced from the original architect’s model. Maintaining the BIM theoretically allows better control of the build, but this is a benefit normally realised only by larger contractors (see 4.5), as summarised by interviewee C2: “to my mind, there is no point having a BIM model that isn't also connected to construction program and cost”. In other words, economic benefits come from maintaining the build speed and being able to invoice clients accurately for the work done. Smaller contractors do not need BIM to do this. A software tool provider remarked that she had only seen “literally a handful of projects” where a sophisticated BIM has been “kept up to date as opposed to being like a 3D visualisation tool” (C4).

5.4 **Government incentivisation of BIM use**

Over the last 20 years or so, government bodies and parastatals have supported the development of BIM by specifying that it must be used in tendering and project work. This has been patchy: the first to do so was the UK government in 2011 for national government work[27], but no other UK edicts exist and it is still possible to tender using pencil and paper for local government jobs. Various property agencies in the Nordic countries also required BIM from an early date, and numerous other government bodies at various levels now require it (examples from interviewees: Latvia, Netherlands, Norway, Slovenia, Spain).

‘Requiring BIM’ has different meanings, from designing the project using BIM to simply producing a BIM at the end of the project, which can be done by designing the project in 3D CAD and contracting a third party to produce an as-built BIM at the end of the job (A18). Respondents were all unclear (or dismissive) about authorities ability to read a supplied BIM, though Latvian interviewees were positive about their municipalities determination to get a BIM education (A15 & A16). Central government edicts requiring BIM for government work have limited effectiveness (and may simply be an expensive overhead) if the local government office cannot read the model (C8). Whilst acknowledging the importance of governments promoting BIM (A16) the usefulness of BIM as a control measure to ensure savings (cost, energy or materials) is currently limited. This lack of familiarity with BIM, and embodied carbon results based on it, is potentially serious for the realisation of CE benefits. Tenders requiring an LCA embodied carbon figure are and will likely always be unregulated: sharp practice in LCA calculations can and does lead to loss of contracts due to lack of understanding by the project owner (C5). Additionally, it is doubtful whether a BIM-derived as-built LCA figure can be supported by an electronic audit trail back to the building materials, and although software is marketed to enable this there is no suggestion of legislation to enforce it (C4). So there is a danger that the LCA result becomes a little understood, checked or supported number of key importance: an unsatisfactory situation. Without understanding and policing of the measure not only are benefits likely to be limited, but the entire system may fall into disrepute.

Laws requiring LCA calculations already exist in Denmark (termed BR18), France (RE2020), Sweden (Swedish Climate Declarations) and Netherlands (MPG). These countries have shown that data extractions from 3D CAD designs may be used to calculate embodied carbon (also C3), but it is more easily done from a BIM extract as this carries more information on each building element. Consequently, this EPBD legislation is likely to drive some architect's firms towards BIM.

5.5 BIM for larger firms

While all the larger firms in this study used BIM as the backbone of their businesses, many interviewees focused on different aspects of its capabilities, from improved design (A15, A16) to communication (A8) to scheduling (C8), perhaps depending on their function within their businesses. It allows multiple users from within and outside the firm to work on the model: up to 100 from 70 different disciplines in recent projects (A2, A17). Post-design, BIMs ability to reduce material usage was regarded as small or incidental (A8, C8).

Enabling collaboration through BIM is perhaps its key feature. This occurs both by direct input into the model and by interchange of data using import and export in a format known as IFC (Industrial Foundation Classes). Model sharing, through IFC or otherwise, commonly involves withholding sensitive parts of the data (such as quantities) for Intellectual Property or competitive reasons (A9, A14, C9, C10). Many consultants cannot yet use BIM models (A12, A16). If they use 3D CAD this can also output to IFC which can then be integrated into the BIM (A10), although the level of detail on each element is much less (A8). Structural engineers in particular do not normally use either of the two main BIM systems (Autodesk/Revit and ArchiCAD) but generally use Tekla; IFC interchange works much better than it used to (A16) but will still result in data issues unless the firms use the same system (A8). Whatever the level of collaboration in a model there need to be strict and well understood rules for governing it (C6): most users conform to BIM data standards (C4). Of relevance to this study, the key point is that the software does not lend itself to rapid input/output of data necessary to iterate a design to minimise total embodied and operational emissions (LCA2), collect real-time building management data from a variety of sensors (C6) or interface with a non-BIM trained user such as a building-site worker or facility manager (C9).

Use of consultants and subcontractors is partly about sharing responsibility (A15): noticeably, all the Dutch architects interviewed use structural consultants for liability reasons (A2, A8, A9, A14) even if the firm has carried out its own structural calculations internally (A14). Legally, architects generally accept that the client owns the completed BIM (A8, A14, A15) and it forms part of the supply of the designed and built structure. Since multiple parties have changed the BIM it could be difficult to prove liability for errors.

All firms set up and use models slightly differently (C10), inputting different data and so not all produce bills of materials (C5) and few utilise scheduling (C4, C7) or the ability to see the building at different stages of construction (C5). For the most sophisticated users, set-up becomes problematic enough that they rebuild or expand the architects model themselves to enable control of construction (C9, C10).

Software 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. However, it does not override professional judgement, which ultimately determines material usage and CE impacts (A16).

Advanced computing is increasing the benefits of BIM to constructors with larger projects by directly connecting the BIM to build progress. Comparison of 360° on-site video to the BIM is now possible by sight (e.g. OpenSpace.ai, Dalux.com; C2) and through video data integration (Buildots.com; C8). Roving printers (ink or laser) can rapidly mark out newly built floors with the precise positions of partitions and services and work well (C6). All intend to increase build speed, mainly through improved accuracy or better progress chasing: benefits to the CE are incidental through minimisation of rework and reduced travel to site. Prior to video integration firms which used the scheduling function for progress chasing did so through manual update from on-site observation (C8). Progress chasing software links the build to the schedule, but not to cost: even in more technically sophisticated firms the accounts function does not generally use BIM for costing, nor for invoicing clients depending on work done (C5). An interviewee remarked that firms don’t make decisions from BIM because they don’t fully trust the data (C4): perhaps this is evidence for this statement.

However, even larger firms using sophisticated computing appear to be the minority. For example, a household-name UK housebuilder interviewed uses 3D CAD for designing and building housing estates and apartment blocks. Furthermore, they believed their level of knowledge was advanced compared to firms they were aware of on the UK Housebuilding Council: “There's a lot of … medium sized house builders [on the Council] that still don't even know what embodied carbon is”, while they used 3D CAD output to analyse whole-of-life carbon (C3).

5.6 Culture and Industry ways of working

It is perhaps well-established that smaller constructors have customary practices and see no need to change either their methods or material types (A7, A12), and nor do they use digital models (A1, A2, A11). Additionally, education is lacking: “I think most architects have no clue...what is the [emissions] impact of the decisions that they make” (A14).

A French interviewee remarked that “We didn’t break the silo between studies and site” (C10), meaning that the connection between architects and constructors was limited. Noticeably, interviews show that vertically integrated companies (those undertaking both design and build) were greater advocates of BIM and digitalisation more generally, and this was not limited to the largest firms. Perhaps the most integrated was a medium-sized Dutch family company with an apparently very stable workforce and sub-contractor/supplier group with established rules for systems use, such as subcontractors having the BIM to tender against (C6 - the same firm planning to drop paper 2D plans entirely). Against this, others noted that the structure of one-off contracts hinder the development of relationships to improve ways of working (also well-established thinking[9]). Additionally, against a backdrop of contracts being delivered late and with 20% cost overruns, even large clients need educating in the benefits to them of paying for improved software to add control (C11), such software use being purchased on a contract-by-contract basis. While not guaranteeing on-time delivery, it could at least explain precisely why it was late, so that it could be fixed for next time – except that there is no next time for this group of collaborating parties (C11). The culture that each contract has to make a standalone profit (C8) has the side effect that it hinders investment in experimentation.

During the research three sources, two being interviewees from different southern European states, flagged serious cultural issues with BIM adoption as construction practice is often to make money from cost overruns and problem rectification. This was described by one as endemic in southern Europe. ‘Culture is singularly persistent” (Peter Drucker, WSJ, 1991) implying that constructors in these states will not welcome the control and transparency that BIM brings and are unlikely to implement it swiftly or thoroughly.

5.7 Digital Knowledge: Skills, Training and Digital Divides

5.7.1 Skills and Training

Generalising across Europe, it appears that architecture students are trained in CAD but not in BIM principles, although (exceptionally) Latvia does (A3, A7, A16). An ex-student from Croatia remarked that a Professor there had never seen a 3D rotation until the students showed him one, and she thought that experience was typical: none of the trainee architects in her firm had experience of BIM prior to joining (A7). Spanish universities do not teach BIM principles: private tuition is necessary to learn (C8), which leads to skills shortages as small firms cannot afford to train staff. A skills shortage exists in Greece, partly because low salaries and a low level of penetration creates a poor training environment (C11). Economic issues – an inability of small firms to afford staff training – also leads to low levels of skills in Spain (C8). A Slovenian interviewee did not think that there was a current skills shortage, but that the decision to pass a law requiring a BIM for new work on public buildings would create one (A18). Almost all interviewees found that recruits needed training to be brought up to company standards when they were appointed (A7, A14, A15, C6) and some purchased external training (A9, A16). Younger staff adapt more quickly whether in architecture or construction (A18, C6) leading to an increased BIM penetration (A18). Generalising, it appears that most of the BIM training is on-the-job and starts from a low base level. No state appears to be producing an excess of BIM-trained workers.

On-site workers do not generally have BIM skills (C10), which is unsurprising given the low penetration of BIM onto building sites. One firm did train in the use of digital tech more generally (C6) without letting their workers change models. Larger firms automating progress chasing were doing so with video capture bypassing any need to train workers in 3D systems input as buildings are built by people “with very low level of education and in some cases they’re not very fluent with the language either” (C8).

5.7.2 Digital Divides

The ‘Digital Divides’ concept refers to skill discrepancies within and between organisations causing hierarchical or other tensions and issues. It is clear from the totality of interviews that there is a divide between smaller and larger firms in terms of the amount and complexity of software used (A3 also made the point specifically). This may be caused partly by the pricing policies of the software houses (A15) but also depends on the ‘techiness’ of the personnel themselves and how much is developed for in-house use (A1, A14). At its simplest, the interviewee who did not use electronic tools could turn to another firm who would assist if necessary (A6).

Within larger architects firms, there is normally 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, eight or nine architects and the rest of the company is the case managers and technical drawers? So they have a bigger vote” (A12).

This split between designers and technical architects is not always present: it depends on the structure of the company. If the technical skillset is high or specialised enough then there is no difference between company members at different seniorities (A14). If there is a split, it is not necessarily a problem: large companies recognise that some employees prefer designing and some are more comfortable using the software: these can both be accommodated (A15).

Two examples were found of firms with relevant digital skills sub-contracting these roles to others for speed and other commercial reasons: one a sole practitioner (to a specialist BIM designer) and the other a large company (for BIM coordination, A15; also A12), highlighting that software specialisms (digital divides) exist across architecture. Concern was voiced that firms not using BIM might not survive long-term (A16).

5.8 Passing on the model to be used in Facilities Management of completed buildings

The handover of a building to the new owner is a time when the use of the BIM may cease. In essence, the BIM holds vast amounts of detailed relationship data, but the Facilities Managers (FMs) only need spatial data plus a look up facility to check parts details for maintenance or replacement purposes. As staff need BIM training to access BIM data not all FMs can work with BIM (C6), though if the constructor is also managing the completed building then the BIM may be used in FM (C5, C6). Access control for updating service history is also an issue (C5). Skilled constructors and consultants can tailor an extract from BIM for various FM systems, if the manager is chosen in advance and their system known (C7, C8). Conversely, if the manger’s system is unknown or the constructors less skilled the passed on a BIM of limited completeness and usefulness (C5, C9) and in general it appears that normally much or all data is lost on handover of the completed building. Getting better data from the BIM potentially impacts long-term material use by marking for reuse (C9) and better maintenance leading to less parts replacement, an important but little-emphasised area as Mechanical, Electrical and Plumbing (MEP) fixtures can amount to 10%-18% of embodied emissions and be replaced every 10-20 years[40].

Likelihood of using the BIM in FM appears to vary significantly 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, C3) “All those fancy models, but real estate management doesn’t take them over” (LCA8, Sweden). ‘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). Note that 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 FM 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 pdf’s 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).

Results

Section B – Findings likely to further the aims of the Circular Economy, or limit it

6.1 Cultural issues affecting the implementation of legislation

At its simplest, building typology is set by local factors: available land, population density and climate (C1, C2). Material usage will vary accordingly. It follows that building codes and practices will vary across the EU: legislating at EU level must recognise need for local discretion, most obviously in the context of this study for embodied carbon limits to differ between climates such as Finland and Greece. The revised EPBD does this[19].

Responsibility for selection of building materials between architects and constructors varies greatly between countries, from architects having almost complete control in the UK (perhaps for perceived liability reasons (C1)), to architects being responsible for the ‘look and feel’ of a design but constructors being almost wholly responsible for materials (LCA3, Denmark; C11, Greece). Subcontractors generally order the great majority of the materials. Within countries there is variation also, depending on the firms and their relationships.

Similar differences exist in BIM production and updating. For example, in Denmark, Netherlands and Slovenia there is written guidance detailing the dividing line between architects and constructors’ responsibilities (A8, A18, LCA2). In Germany, the architect has greater responsibility for updating the construction model (LCA2), which would be counter-cultural elsewhere. These issues impact interpretation of LCA legislation into practice: calculations at planning and completion will be prepared by different parties and with far more detail potentially available at completion. Even within the pioneering 4 states, each has different legislation.

Different states also have different attitudes towards granting permissions for live testing of new materials, with some more flexible than others (C10). Also, local market norms govern or influence new material use: for example, a Dutch interviewee remarked that their firm’s wooden houses had to look conventional to be sold, so they were faced with thin ceramic tiles which looked like bricks (C5), negating some climate benefits of using wood.

6.2 Green Certifications

Only some clients are interested in sustainability, and architects will follow their clients lead (A15, A16, A17). While some firms are approached to undertake work because of their reputations for sustainability (A6, A14) interviews suggested that the clear driver of reduced GHG emissions in commercial buildings is institutional investors valuing certified buildings more highly (C2, LCA1) in no small part because tenants are demanding it (C2, C11) and many completed buildings will be sold to pension funds whose contributors also demand it (C2). Tenants are sensitive to their employees demands for them to do 'the right thing' for the environment, and working in a low carbon building attracts employees (C2). So developers are driven towards green certifications for their buildings. 'Green Certifications' are standards such as BREEAM, LEED, DGNB and the EU Taxonomy, all common in Europe, which cover both operational emissions (also covered by legislation) and embodied carbon (which is so far only implemented into law in 4 member states).

Certification involves higher costs, and BIM will be necessary to complete the data requirements for any of these standards (Veselka et al., 2020) (also A3, A16). Both architect and constructor need to use BIM (A3). DGNB requires a Life-Cycle Analysis (LCA) calculation, for BREEAM an LCA is useful: LEED does not require one[41]. These add value though two mechanisms. Firstly, lower operational energy requirements reduce occupant outgoings so permitting rentals to be higher for the same total cost to the occupier (LCA1, LCA9): the capitalised value of the additional rent creates value. Secondly, in oversupplied markets certifications provide comfort against obsolescence for property investors and for banks (LCA11), so loan finance is significantly easier to obtain (LCA9, LCA11) and possibly slightly cheaper (LCA9, LCA10). It is unclear (to developers or banks) whether reduced embodied carbon leads to a higher building value, as it is neither visible or tangible to the occupier, nor does it create an obvious market signal (such as lower running costs) (LCA9, LCA11), and there are very few completed transactions upon which to form a judgement (LCA11). 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 carbon levels (LCA9, LCA11), and clients are thinking carefully about whether to build to today's standards or those they perceive may exist in 5 years' time (LCA1).

6.3 Life Cycle Analysis legislation

The study focused on Denmark as an exemplar, with additional input from Swedish, Dutch and French interviewees.

6.3.1 Outline

Life Cycle Analysis (LCA) of buildings estimates its contribution to GHG emissions throughout its life, from the build through its occupation and use, including maintenance, repair and replacement, through to dismantling or demolition. The numerical result is normally expressed in kilogrammes of CO_2 equivalent gases per square metre of floor space per year of life - kg CO_2e/m^2/year: to date, a 50 year life has normally been assumed and this is now set in legislation[19]. While detailed numbers may be known for the GHG content of materials (such as cement), many of the other figures (operational energy usage, for example) are projections or estimates: guidelines exist for their calculation so that the end results are as comparable as possible.

Four EU member states – Denmark, France, Sweden and the Netherlands – have passed LCA legislation. Each has an initial mandatory phase where results merely have to be reported: this forces firms to develop and refine their data collection, calculation and reporting processes, allows manufacturers to produce embodied carbon information for their products which will be incorporated into the buildings, and allows software houses to develop products to integrate output from 3D CAD or BIM systems with external EPD databases to calculate the LCA result. (The product manufacturers statements of embodied carbon are called Environmental Product Declarations, or EPDs).

Following the introductory period, mandatory limits will apply, meaning that new developments will have to be planned to deliver below-limit buildings and an as-built model will be required to enable calculation of the final LCA. The final LCA will need to be below the limit or the building will not receive an occupation permit. Limits ratchet downwards over time.

Each of the four states schemes differ in terms of methodology and areas of inclusion or exclusion: Table 1 gives the main details. Three simply measure GHGs: the Dutch standard (called MPG) also includes measure of environmental damage such as toxicity and eutrophication and is expressed in €/m^2/yr. This is less intuitive as a GHG measure (C5).

6.3.2 Politics and Practices

While the situation in each of the four states is different, the result in each has been that the first mandatory limit will be loose and impact relatively few properties (LCA3, LCA9), generally those over 1000m^2 and developments of over ten homes, before the second phase (2027-2030) tightens the limits to a point where they would appear to impact significantly (C10) and extend the coverage to most property types. Repairs and renovations are generally excluded. To reiterate the point made in the Introduction, the passing of the recent European Property Buildings Directive[19] post-dates the four states legislation and mandates all member states to have a road map in place by 1st January 2027 to enforce limits on LCA totals by 1st January 2028 for buildings over 1000m^2 and by 1st January 2030 for all buildings, including domestic, such limits to have a progressive downward trend.

The EU is driving change at speed, but it is unclear how prepared governments and the AEC industry are. While one constructor interviewed produced embodied emission calculations as standard for their own information to assist their drive to Net Zero (C11), this appears as an outlier. Three examples from this study demonstrate possible issues. Firstly, there is a general lack of awareness about the near future amongst the specialists who will have to lead the changes. Interviewing Swedish architects about their own LCA legislation, two claimed to barely have heard of it (LCA6, LCA7). Similarly, Dutch and Norwegian architects were unaware of the Danish Regulations (A2, A3). Secondly, as noted above a UK housebuilder referred to most smaller housebuilders that “don't even know what embodied carbon is” (C3) indicating a very low knowledge base needing rapid development. Thirdly, it is not sufficient to pass legislation in Brussels and in member states capitals: it needs the support of the industry and also considerable training resources. This is illustrated by Spain, where a central government edict that an as-built BIM was required for government work is in place but unsupported at lower levels: many local government authorities do not have the relevant software licences and cannot open the models they are sent (C8). Similarly, Danish and Dutch municipalities do not have the expertise to assess LCA or MPG calculations (LCA4, C5). Without controls in place, the potential for poor practice to develop, bringing the process into disrepute, is high.

More positively, interviewees in Belgium, Latvia and Slovenia (A16, A17, A18) expected their governments to follow France, Denmark, Sweden and the Netherlands in passing embodied carbon regulations, but their governments now have their hands forced by the EU. These interviewees regarded BIM as necessary to enable detailed embodied carbon calculations, although 3D CAD can be (and is) used (C3). Whether or not some smaller architects firms, who predominantly use 3D CAD, switch to BIM, the requirement to produce GHG calculations will be a significant process change. Alongside this, it may also be necessary to specify the precise supplier and type of material for each element, in order to allow the software to collect the correct EPD, rather than a generic element which will probably carry a 20%-30% higher GHG figure (C5, LCA8).

For constructors the changes will be significant. As stated above, few have experience of using a 3D CAD or BIM model and many workers are poorly educated (C2, C8). In future, they will have to take a model, probably from an architect, and update it to as-built status, before the LCA can be calculated by themselves or a consultant. A potential work-around is for the constructor to update 2D paper plans and the architect to update the model (C8). The accuracy of the as-built model is an open question (LCA2). The change will also impact on materials selection: it may no longer be sufficient for architects to largely delegate this to constructors as happens in many states, such as Sweden (LCA8). Over time, as limits tighten, the specific materials selected at the planning stage will have to be those used in the construction: a significant practice change. In states such as Denmark where the practice is for architects to produce the ‘look and feel’ of a building and constructors complete the detailed design and construction, these two may have to become more integrated to ensure compliance with the LCA limit (LCA1, LCA2).

6.3.3 Cultural impacts

In Denmark, LCA legislation has ‘changed the landscape’ of the industry: everyone understands LCA and knows what it means from investors to suppliers. There has been a huge shift in people’s views and a rush by suppliers to produce EPDs (LCA4, also LCA9). This would not have been possible without the legislation (LCA5). Some interviewees voiced a real sense of urgency and lack of time to solve the embodied carbon issue (LCA1, A14). This is all very positive, but comes from individuals deeply concerned about carbon emissions. It is not possible to say how reflective this is across industry.

There will be some uncomfortable changes: the future role of Quantity Surveyors was questioned if digitalised systems are used systematically to produce accurate LCA calculations, and so could produce accurate Bills of Materials, currently uncommon (LCA1, A7). Smaller firms may face challenges and need to specialise to survive (LCA1, LCA2), although shortly there will be more software and graduating students with new skills, so the impact may be less than it appears (LCA3). In Sweden, specialist carbon calculating firms have sprung up, producing LCAs from material quantities or digital outputs, for firms unwilling or incapable of producing their own (LCA8). There is a general tendency of governments to over-complicate the level of required detail in reporting (LCA2).

Current tendering practices may also be impacted, as these often do not include fully completed designs. For example, in Denmark, tendering uses plans excluding smaller items, such as door handles and door glazing, which fits awkwardly with the need to approve plans under LCA legislation (LCA2). These difficulties need addressing by the industry and authorities (LCA2).

6.3.4 Calculation method; principles and issues

As noted above, each of the four member states with enacted laws differ in their rules and exemptions: they also differ in calculation method. Using Denmark as an example, the rules are set down in LCA Byg (lcabyg.dk), developed by the Danish Institute of Building Design, but not integrated into BIM. Third party application developers are bridging this gap, with firms of all sizes trying to work out which is the best software product to use (LCA3, LCA5). Any application has to link an extract of a model from CAD or BIM to a database of EPDs and the specific calculation routine for that country. “I think every company with the more than 100 or 50 people they've been sitting developing their own calculation tools” (LCA2).

France and the Netherlands have their own national databases of EPDs; calculation methodologies are necessary to keep entries comparable, which can feel bureaucratic to users (C5) although there is some concern that EPDs are manipulated by manufacturers (LCA2). The Danes and Swedes do not have national databases (LCA1, LCA2, LCA9): firms are creating their own at much (duplicated) cost (LCA1), or sourcing from paid-for databases (LCA5), or using the German Őkobaudat database for sample product data at the early stage when there is much uncertainty about the final product materials (LCA3). Database data can include bio-based, organic and timber materials, whose suppliers are all producing EPDs (A14, LCA5). Suppliers are being pushed to produce EPDs by architects as without one there is less chance that the product will be incorporated in the design (LCA8) as architects are obliged to use generic EPD numbers for items they do not have specific EPDs for: the generic EPD number are typically 30% higher (C5).

The ideal of an iterated solution to minimise the total of operational and embodied energy, subject to cost, is difficult with BIM systems because of its inability to take an automated feed as input (C7, LCA2). 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'* [42].

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. By-passing this problem with an automated process to get 'the best' declaration is an aim being progressed, but it is not clear how practical it is (LCA8).

The revised EPBD sets out the timetable for introduction of EU-wide LCAs: it clarifies that a 50-year life will be standard in the calculation, which some saw as arbitrary and open to debate (LCA4). However, as it leaves the calculation methodology open for development by individual states to address local climate and building methods, it also leaves open the inclusion or exclusion of items such as groundworks, surface finishes and ventilation systems (LCA2), the level of detail required [using BIM with a high level of detail simplifies the calculation (LCA5), but specifying a high level of detail could be prejudicial to those not using BIM], and the treatment of reused and recycled components and those designed for deconstruction. Reused and recycled materials are currently included as carbon-free (LCA4, LCA5).

3D CAD can export data on quantities by material type, which can be combined with external data to produce an LCA calculation. However, these quantities are likely to be less specific than those from BIM, where individual elements may have already been linked to a manufacturers EPD. If generic EPD figures are applied to these quantities it raises questions about accuracy of the resulting LCA: how accurate it needs to be remains an open question.

6.3.5 How effective has the legislation been in causing design & construction practice changes?

This section refers primarily to Denmark specifically as it was chosen as the exemplar.

The short answer to the question is 'Not': perhaps better expressed as 'Not yet'. While there has been a widespread change in attitude of AEC professionals (LCA4), in production of EPDs (LCA4) and in the availability of software to perform the LCA calculation (LCA3, LCA5), the limit of 12 $kgCO_2e/m^2$/year is loose enough that little practical change in design has yet occurred. "Most of us also know that 90% of what we're doing anyway, it's gonna be a compliant to 12 LCA" (i.e. the 12 $kgCO_2e/m^2$/year limit) (LCA1).

It was suggested that the Danish government thought 12 $kgCO_2e/m^2$/year was ambitious as a result of lobbying by the concrete industry (LCA3), but that actually 6 $kgCO_2e/m^2$/year is achievable over time (LCA2), and that already most residential buildings are already around 8 $kgCO_2e/m^2$/year (LCA3). Currently, it is impossible to envisage a situation where the architect would realise that the limit would be breached and have to iteratively redesign his structure to meet it (LCA2). "From what I've been hearing, it's really no, it's not a big deal in Denmark to meet that target" (LCA2, also LCA4). Firms that use low carbon materials know from doing previous LCAs that they will be inside the limit (LCA5).

Initial impact has also been lessened because the law only applies to new building permits from 1st January 2023, which creates a long lead time for implementation, and it does not currently apply to renovations or extensions (LCA5).

In Sweden, while the implementation method is different there is also no current impact: until 1st July 2025 the LCA result has to be declared but there is no legal limit, after which the limit will be set at the 75th percentile of the declared results[28]. Currently the calculations are carried out after the event and there is no impact on design (LCA8). In both countries interviewees expected changes to design and construction if the limits are tightened (or set) as planned in 2025 in Denmark and Sweden respectively.

In the Netherlands, some specialist firms are delivering to an 'MPG-less' standard, such as one working to MPG less 30%-60% depending on building type (C6). The firm used BIM in every job and iterated the initial MPG calculation to produce a satisfactory result, then recalculated it after every design change to ensure that the target was still achievable. However, currently the MPG is often calculated post-planning, making it unlikely that the design will be changed if the result is unsatisfactory (A14).

In France, mandatory limits will tighten in 2028, which will be "difficult" for industry (C10).

6.4 Use of New Materials to reduce embodied carbon in the building.

6.4.1 Background

Whether the architect or constructor selects materials varies considerably by country, as noted above in section 5. In some countries, architects select nearly all the materials, perhaps for perceived liability reasons (such as the UK, Croatia) (C1, C7), in much of Europe the constructors have more discretion (C2), and it can vary from job to job, with architects sometimes specifying material qualities and looks but leaving the final choice to the constructors (e.g. Netherlands, Belgium) (C5, C9) or it can be done mutually (e.g. Netherlands) (C6). In Greece, materials are normally specified by the subcontractors unless anything unusual is required, in which case the material determines the choice of subcontractor (C11). Load bearing elements are normally predetermined by architects (UK) (C1). If materials are selected by several parties it limits the chances of iterative modelling to achieve a minimum total embodied and operational emissions (A2).

The chosen materials tend to be traditional, and are based on cost not environmental benefit (A9, C1). "Typically, the …. better for the environment the product is the more expensive it is" (C1). The industry is notorious for being slow to change (A2, [43]), and most clients are unaware of non-traditional methods and materials (A2), reducing external pressures to change. While the final choice is the clients (A9), they often shy away from using new materials when a consultant points notes potential issues such as unclear durability (LCA2). Architects specifying non-standard materials create constructor discomfort, who try to put customers off using them (A12) as constructors generally have a lack of interest in changing work practices (A2). The effort of trying to persuade builders and clients to use new materials saps creativity and so ultimately time, money and knowledge mitigate against use of new materials (A12).

6.4.2 Building Structure

Structural elements hold 45%-55% of total embodied emissions in a building [44]: reducing this is key (A2, A14). In response to specific questioning, interviewees mentioned steel, low emission cement and Cross-Laminated Timber (CLT) as alternatives to reinforced concrete, with steel acknowledged as high carbon (C5, C10, LCA5). Some 'low-emission cement' uses the standard Ordinary Portland Cement chemical reaction to form the binder, but is claimed to use 'recycled' cement and be low emission on that basis: building codes allow it to be used (C6, [45]). Building codes are set around the properties of conventional concrete (C10) which excludes most low emission cements. Generally, 'low emission cement' is an umbrella term for cements either

(i) where up to 20% or exceptionally 30% of the clinker (the active ingredient) is substituted by other materials such as Ground Blast Furnace Slag, Calcined Clay[46] or Ground Bottle Glass (sioneer.com), or

(ii) not using the same chemical reaction as Ordinary Portland Cement in their binders, such as alkali activated cements. These are expensive, but on average have 50% lower embodied emissions[47], and currently need approval on a case-by-case basis for specific applications (C10). Some jurisdictions grant approval more readily than others: for example, in the UK "no one wants to take any responsibility" (C10). The use of steel is being investigated as an alternative to reinforced concrete in structures (C3), and some prefer it to CLT in principle (C2) ("The long-term solution to lifetime carbon reduction is buildings that last a long time"). Neither clinker substitution nor steel will produce the level of GHG savings ultimately required for Net Zero.

6.4.2.1 Cross Laminated Timber (CLT)

As using CLT as a structural material will almost automatically keep the building within the limit (LCA5), interviewees were specifically asked about CLT. Several use it (A2, A3, A8, A10, A18) and 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 (LCA3) and the closest CLT factories are in Sweden and Austria (LCA4), signalling supply issues if CLT use becomes widespread to keep the building within embodied emissions limits (LCA5). The market may remedy this: 'Everyone' is setting up factories for wood (C5, Netherlands).

However, CLT has drawbacks. After the Grenfell Disaster in the UK (a fire in 2017 which killed 72 people in a conventionally-constructed 24-storey apartment block), CLT's perceived fire risk is an issue (C2, C3), even though it is not a problem – the outside of CLT chars and hinders further combustion (C1). Regulations vary across Europe (Figure 3): in some states, regulations require that

CLT has to be faced with another material for fire reasons, regarded as unnecessary (C5, Netherlands). CLT has a better fire safety rating than steel beams of similar load bearing capacity, as the steel loses its strength when heated[48].

CLT is lighter than concrete, so (for example) wood floors offer savings in weight which enables economies of materials in the load bearing structure. However, this is to some extent offset by the acoustic transmission of wood, necessitating the addition of other materials to dampen this down (C1, C10). It may not be easy to find a supplier ("Getting the right spans is difficult") (C2) and has the practical difficulty that it cannot be changed on site (C1). CLT is also not a good insulator.

Analogous to the difficulty of BIM implementation, which means higher initial cost and returns later during the build, structural use of CLT means higher design costs and a far swifter structural build, offering immediate payback (A2). Additionally, an interviewee was clear that any perception that CLT is more expensive to build in than concrete is wrong, and when carbon border taxes are applied to cement any difference will be eliminated (LCA8).

So there are various arguments for and against CLT, but it is being used in practice to build multi-storey apartment and office blocks in multiple European countries. For example in the Netherlands[49], in Sweden[50] and in the UK[51].

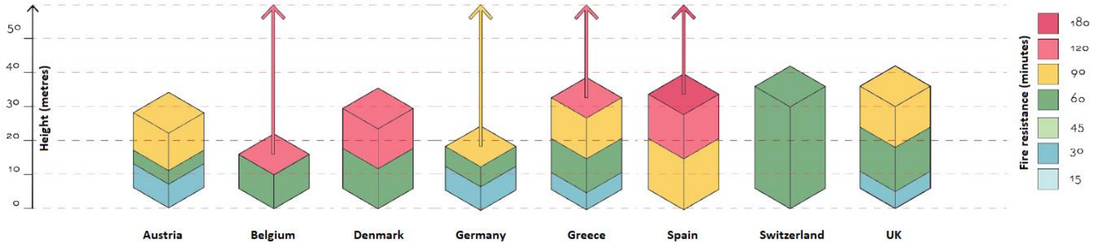


Figure 3: Variation in European fire resistance regulations – without sprinklers

Source: Waugh Thistleton Architects

6.4.3 Non-structural Building Materials

Some highly beneficial changes can be made without influencing the design at all, for example choosing bio-based material for the non-load bearing interior walls (A14). Not all bio-based materials have to be wood: anything that's stringy and grows, such as tomato plant waste, straw and bamboo can be used to make boards or insulation. They all sequester CO2 (C5).

Offsite modular construction of non-structural units is enabled by BIM. The architect's BIM and the factory BIM are compared and incompatibilities solved before production (A8). The main driver of modularisation is on-site time saving as modularisation is not significantly cheaper than on-site building because of factory set-up costs (C2). It saves materials, but for a constructor, quantifying the material savings in comparison to an on-site build is difficult (C8). Modularisation makes the embodied emissions calculation easier (C10). Units are unlikely to be fabricated from concrete: the weight saving leads to savings in the structural materials, whether or not conventional reinforced concrete is used (A14). Module fabrication can be at sub-room level, such as a wall with built in lighting and storage, rather than whole-room which may give more flexibility and better economics (C10). One firm was experimenting with producing packs of parts and fixings, together with printed instructions, for delivery to site to make certain building operations more of an IKEA-style assembly operation, again to save time though with upsides in reduced on-site cutting, waste and accidents (C10).

6.4.4 Commercial and Regulatory issues around new and reused materials

6.4.4.1 Regulations

Historically, regulators have been slow to approve new materials, and this continues (LCA2). There is variation in regulators attitudes across Europe, both for experimentation and for final approvals, for example the French being more willing to grant experimental approvals than in the UK (C10). Safety is critical, but to reduce embodied emissions, approval of new and reused materials on a speedier basis then hitherto is important.

Fire risk is the major regulatory problem with reused materials (LCA5).

6.4.4.2 Insurance and Warranties

In broad terms, new materials will have uncertain lifespans, but the need for drastic emission reduction implies that new materials must be installed. The resulting insurance and warranty problems are obvious "but we just need to solve it" (LCA1). There is a similar problem with reused materials (LCA5, [3]). So if steel beams from a building are removed, individually subjected to testing and resold, an insurance company will need to cover them: a nascent market, currently. It is difficult to find trios of owner/architect/constructor willing to incorporate such products (LCA3). There is clear acknowledgment that these issues are difficult and need resolving (LCA1, LCA2).

6.4.4.3 Economics of reuse and Deconstruction

The construction industry is starting to reuse some materials and fixtures (such as facades, ceiling tiles or raised floors) but there is a challenge to remove them, store them and refurbish them while remaining cheaper than buying new (A17, C2). If it is used in a new build, it counts as zero carbon in current calculations (C2). Reuse is hindered by demolition not being digitised (C3, C11). Some voiced scepticism that reuse will ever be a reality (A8).

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[52]. Additionally, the commercial processes to centralise knowledge of used product availability are limited (A17) and only now being established: though one firm interviewed has an algorithm to auto-match available steels to new designs (C11). Long timescales inherent in designing and permitting new buildings around used products inevitably involves storage and reduces viability.

6.4.4.4 Design for Deconstruction

Design for Deconstruction did not find favour with interviewees. Firstly, there is a crisis with GHGs now: "it's more important that we focus on the emissions that we are creating now than to create a building that maybe you can totally take apart in 75 years' time" (A14). Secondly, architects struggled to give credence to reusing old materials after several decades of use (A8). However, UK Local Authorities require developers making planning applications to show that they have considered deconstruction (C3). More positively, two interviewees noted how useful BIM was in designing and dismantling buildings or interiors intended to be temporary (A2, C7).

7. Conclusions

The study set out to establish if increasing digitalisation across the Architecture, Engineering and Construction sector is likely to facilitate the CE in terms of materials use: reducing embodied emissions by better choices, using less material and lengthening useful lives. It found in large part a settled pattern of digital adoption, either high-tech (BIM and tools) or lower tech (3D CAD) amongst architects. Constructors predominantly worked from 2D plans without BIM, though with larger firms pushing at digital boundaries.

Use of digitalisation through BIM to contribute to the CE depends largely on the motives of the users – to incorporate new lower-emission materials – and on the sophistication of the model and consequently its ability to act as a tool to deliver control, implying better specification of bills of materials, improved clash detection and less rework. The interviews suggest that regulations have delivered steadily lower operational emissions but that lowering embodied emissions through better choice of materials has until recently been limited to a few environmentally orientated firms.

New LCA regulations in Denmark, France, Sweden and the Netherlands, to be followed across the EU by 2030, are potentially game-changing for embodied emission reduction. The LCA calculation is enabled by digitalisation, either 3D CAD or BIM, plus LCA calculation software and EPD databases. Nearly all new European buildings are designed on 3D CAD or BIM. Interviewees in the four impacted states were wholly in favour of the legislation, but political support has to exist for emission limits to reduce and technical difficulties to be ironed out. At this early stage, the results suggest that there has been a widespread positive revision of ideas, which is perhaps the most significant indicator of likely success. Alongside this, the rapid creation of EPDs by manufacturers and software to enable easier calculation of the LCA suggests that technical issues with performance of the calculation will be rapidly overcome. Furthermore, LCA offers a method of ensuring that expected 'design efficiencies' incorporated in third parties modelled projections are realised. Governments now have to follow through and implement limits which will force design and practice changes by architects and constructors respectively. Interviewees suggest the authorities have a current inability to understand, monitor and enforce correct calculations, which if it continues will at best reduce the effectiveness of the legislation and at worst bring it into disrepute as a control mechanism. Implementing LCA regulation in states with limited digitalisation of construction is a long-term process involving education and change of practice: change will not happen simply by writing new regulations.

There are some specific limitations to the study. Firstly, the number of interviewees, spread across the whole of Europe, necessarily limits generalisability of results. Secondly, despite attempts to contact architects and constructors uniformly across Europe, northern states are over-represented: the likely reasons being that the technical language in these states tends to be English, and that potential interviewees in states with lower levels of digitalisation are less likely to respond to requests for an interview to discuss it. It is also the case that there are fewer interviews than desired with firms which did not use BIM: these interviews were harder to obtain. Conversely, there is a probable over-representation of technophiles, but this does show the potential, or otherwise, for the software to contribute to the CE.

Further research is needed to establish how compliance to the EPBD (LCA for all new buildings) can be achieved across the EU by 1st Jan 2030 as planned[19], while minimising disruption and cultural resistance from constructors and obtaining understanding and control of construction data by local authorities.

Appendix 1

Quantifying the impact of LCA legislation on embodied energy savings and net zero targets

While modelling of embodied emissions of European building stock is undertaken it is complex: for example, Röck et al (2024) use 60 different building archetypes representing different building typologies and energy performance levels. The difficulty of establishing existing embodied emission levels at a granular level impacts policy: for example, in the absence of data the Swedish government are collecting embodied emission information on new builds for 3½ years to enable them to set legal limits at the 75th percentile. The distribution of the data will change once limits are imposed, but how and how fast are unknown, considering that imposed limits theoretically affect only overlimit buildings but limits induce innovative practices and many under-limit buildings will adapt to the changing environment by also reducing embodied emissions. Also, as different climates impact local building practices existing data for one member state is not generalisable[53]. Existing studies, likely based on different methodologies, show widespread levels of embodied emissions in dwellings, from 380 KgCO$_2$e/m^2 (Italy, [54]) through 396 KgCO$_2$e/m^2 (Norway, [55]) to 720 KgCO$_2$e/m^2 (Denmark, [54]). Taken together, quantification of savings from LCA legislation can only be inexact.

Appendix 4 gives a derivation, based on the averaged aims of published targets in the 4 states with existing legislation, suggesting 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 to come if targets are tightened. This assumes no building types are exempted from the limits. Table 3 shows a derivation of the annual impact in MtCO$_2$e. There is overlap between reductions driven by LCA legislation and reductions in other studies through projected design efficiencies (particularly in cement and steel), such as those estimated at 20% to 2050 by the UK Green Building Council [56]; however the LCA legislation could be considered the key to unlocking these savings in practice.

Using Ramboll (2023) using EU emissions figures from 2020.

41% of EU emissions were from buildings, totalling 1360 MtCO$_2$e.
21% of this is embodied emissions & 79% is operational emissions.
Of the 21%, 71% relates to new buildings.

So 6.1% (being 41% x 21% x 71%) of EU emissions are embodied emissions from new buildings

A 21% to 31% saving from LCA legislation is 1.3% to 1.9% of all EU emissions or 43-63 MtCO$_2$e.

Table 3: a derivation of potential impact of LCA legislation on total annual EU emissions expressed in MtCO$_2$e

Derivation of a figure for the potential impact of published LCA targets on new buildings for the 4 states with legislation

Published statements of intent:

Denmark	2023 12.0 limit	2025 10.5 limit (12.5% down)			2027 9.0 limit (25% down)			2029 7.5 limit (37.5% down)	
Netherlands	2018 €1.0 limit	2021 limit €0.8 (20% down)			2027 est limit €0.65 (35% down)			2030 est limit €0.5 (50% down)[1]	
Sweden	1.7.25	75th percentile, enforced from 2027			2030	40% down on 2027 limits		2043 80% down on 2027 limits	
France:			2022-24	2025-27	2028-30	2031-->	2025-27	2028-30	2031-->
Industrial and terraced housing:			640	530	475	415	-17.2%	-25.8%	-35.2%
Flats:			740	650	580	490	-12.2%	-21.6%	-33.8%

Turning this into grid form:

	2024	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**
Denmark		-12.5%	-12.5%	-25.0%	-25.0%	-37.5%	-37.5%	-37.5%	-37.5%	-37.5%
Netherlands	-20.0%	-20.0%	-20.0%	-35.0%	-35.0%	-35.0%	-50.0%	-50.0%	-50.0%	-50.0%
Sweden	-10%	-10%	-10%	-10%	-10%	-10%	-50.0%	-50.0%	-50.0%	-50.0%
France		-17.2%	-17.2%	-17.2%	-25.8%	-25.8%	-25.8%	-35.2%	-35.2%	-35.2% [3]

Turning this into 'years from policy inception' rather than calendar years

The first three years from date of policy inception are a preparation: by year ten the policy is biting in full

	Year 1	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 6**	**Year 7**	**Year 8**	**Year 9**	**Year 10**	**Year 11**	**Year 12**
Denmark	0	0	0	-12.5%	-12.5%	-25.0%	-25.0%	-37.5%	-37.5%	-37.5%	-37.5%	-37.5%
Netherlands	0	0	0	-20.0%	-20.0%	-20.0%	-35.0%	-35.0%	-35.0%	-50.0%	-50.0%	-50.0%
Sweden	0	0	0	-10%	-10%	-10%	-10%	-10%	-50.0%	-50.0%	-50.0%	-50.0%
France	0	0	0	-17.2%	-17.2%	-17.2%	-25.8%	-25.8%	-25.8%	-35.2%	-35.2%	-35.2%

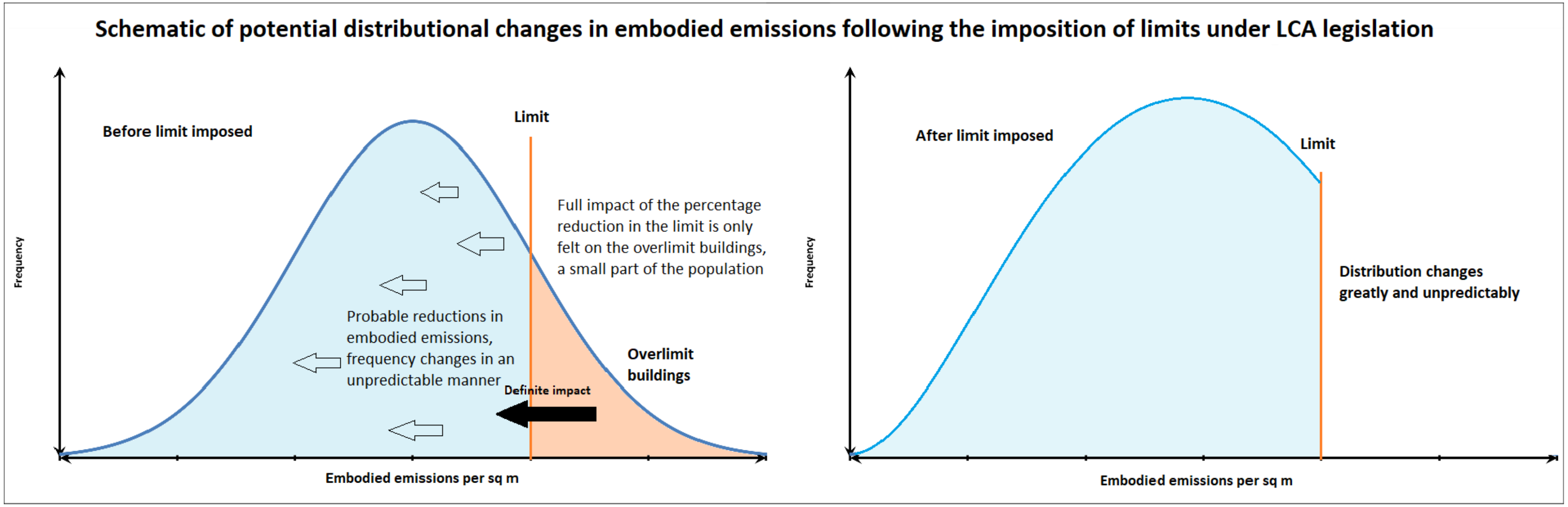
Apply weights:	**Weight[2]**	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 6**	**Year 7**	**Year 8**	**Year 9**	**Year 10**	**Year 11**	**Year 12**
Denmark	0.102	0	0	0	-0.013	-0.013	-0.026	-0.026	-0.038	-0.038	-0.038	-0.038	-0.038
Netherlands	0.264	0	0	0	-0.053	-0.053	-0.053	-0.092	-0.092	-0.092	-0.132	-0.132	-0.132
Sweden	0.156	0	0	0	-0.016	-0.016	-0.016	-0.016	-0.016	-0.078	-0.078	-0.078	-0.078
France	0.478	0	0	0	-0.082	-0.082	-0.082	-0.123	-0.123	-0.123	-0.168	-0.168	-0.168
	1.000	0.0%	0.0%	0.0%	-16.3%	-16.3%	-17.6%	-25.7%	-26.9%	-33.2%	-41.6%	-41.6%	-41.6%

[1] declared aim is to get to 50% saving by 2030

[2] Weighted by size of architects income, Architects Council of Europe, Survey 2020

[3] Using the Industrial figure, likely to cover the majority

Appendix 4 Derivation of a figure for the potential impact of published LCA targets on new buildings for the 4 states with legislation - continued



Schematic of potential distributional changes in embodied emissions following the imposition of limits under LCA legislation

Figure A4: An illustration of the likely movement in distribution of embodied emissions after a limit is introduced

Actual realised reduction percentage

As the lowered limit will impact the highest embodied emission buildings most, the impact on the whole population of new builds will be less than this derived percentage. However, the logic is that the part of the population already below the new limit will reduce emissions also as limits induce innovative practices. Without any knowledge of the per m² distribution of embodied emissions, assume a fraction of the derived reduction percentage is actually realised in the whole population, as an average. This is purely an educated guess.

Assume this percentage is 66%

Then the reduction profile from date of policy announcement in any member states embodied emissions for new buildings are:

Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12 =>
0.0%	0.0%	0.0%	-10.8%	-10.8%	-11.6%	-16.9%	-17.8%	-21.9%	-27.5%	-27.5%	-27.5%

Changing the realised reduction percentage in the population as a whole from 50% to 75% changes the derived overall impact from 21%-31%.

Bibliography

(1) Ramboll. *Supporting the development of a roadmap for the reduction of whole life carbon of buildings. Ramboll Management Consulting for the EU.*; 2023. https://op.europa.eu/en/publication-detail/-/publication/923706b7-8f41-11ee-8aa6-01aa75ed71a1/language-en.
(2) Boverket. *Regulation on climate declarations for buildings: proposal for a roadmap and limit values*; 2020. DOI: ISBN pdf: 978-91-7563-731-0.
(3) HoC. *House of Commons Environmental Audit Committee: Building to net zero: costing carbon inconstruction*; 2022.
(4) Vasakronan. *Impact Report, Green Financing*; 2023. https://wwwvasakronanse.cdn.triggerfish.cloud/uploads/2024/04/vasakronan-impact-report-2023.pdf.
(5) National Grid. *How much of the UK's energy is renewable?* 2023. https://www.nationalgrid.com/stories/energy-explained/how-much-uks-energy-renewable (accessed.
(6) Walasek, D.; Barszcz, A. Analysis of the Adoption Rate of Building Information Modeling [BIM] and its Return on Investment [ROI]. *Procedia Engineering* **2017**, *172*, 1227-1234. DOI: https://doi.org/10.1016/j.proeng.2017.02.144.
(7) Çetin, S.; Gruis, V.; Straub, A. Digitalization for a circular economy in the building industry: Multiple-case study of Dutch social housing organizations. *Resources, Conservation & Recycling Advances* **2022**, *15*, 200110. DOI: https://doi.org/10.1016/j.rcradv.2022.200110.
(8) Mirarchi, C.; Lucky, M. N.; Ciuffreda, S.; Signorini, M.; Lupica Spagnolo, S.; Bolognesi, C.; Daniotti, B.; Pavan, A. An Approach for Standardization of Semantic Models for Building Renovation Processes *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.* **2020**, *XLIII-B4-2020*, 69-76. DOI: 10.5194/isprs-archives-XLIII-B4-2020-69-2020. Huang, B.; Lei, J.; Ren, F.; Chen, Y.; Zhao, Q.; Li, S.; Lin, Y. Contribution and obstacle analysis of applying BIM in promoting green buildings. *Journal of Cleaner Production* **2021**, *278*, 123946. DOI: https://doi.org/10.1016/j.jclepro.2020.123946. Muller, M. F.; Esmanioto, F.; Huber, N.; Loures, E. R.; Canciglieri, O. A systematic literature review of interoperability in the green Building Information Modeling lifecycle. *Journal of Cleaner Production* **2019**, *223*, 397-412. DOI: https://doi.org/10.1016/j.jclepro.2019.03.114.
(9) Andersson, R.; Eidenskog, M. Beyond barriers – exploring resistance towards BIM through a knowledge infrastructure framework. *Construction Management and Economics* **2023**, *41* (11-12), 926-941. DOI: 10.1080/01446193.2023.2218498.
(10) Jacobsson, M.; Linderoth, H. C. J.; Rowlinson, S. The role of industry: an analytical framework to understand ICT transformation within the AEC industry. *Construction Management and Economics* **2017**, *35* (10), 611-626. DOI: 10.1080/01446193.2017.1315148. EMF. *Ellen MacArthur Foundation: Towards a Circular Economy*; 2013.
(11) Waqar, A.; Othman, I.; Saad, N.; Azab, M.; Khan, A. M. BIM in green building: Enhancing sustainability in the small construction project. *Cleaner Environmental Systems* **2023**, *11*, 100149. DOI: https://doi.org/10.1016/j.cesys.2023.100149.
(12) Ness, D. A.; Xing, K. Toward a resource-efficient built environment: A literature review and conceptual model. *Journal of Industrial Ecology* **2017**, *21* (3), 572-592.
(13) ECTP. *European Construction Technology Platform, Digital Built Environment Committee: Horizon Europe 2022-2027 Position paper*; 2022.
(14) Han, D.; Kalantari, M.; Rajabifard, A. Building information modeling (BIM) for construction and demolition waste management in Australia: A research agenda. *Sustainability* **2021**, *13* (23), 12983. Schamne, A. N.; Nagalli, A.; Soeiro, A. A. V. The use of BIM to automated construction and demolition waste management: A literature review from 2009 to 2020. *Revista Brasileira de Gestao Ambiental e Sustentabilidade* **2022**, *9* (21), 377-394.

(15) Nikmehr, B.; Hosseini, M.; Wang, J.; Chileshe, N.; Rameezdeen, R. BIM-Based Tools for Managing Construction and Demolition Waste (CDW): A Scoping Review. Sustainability 2021, 13, 8427. s Note: MDPI stays neu-tral with regard to jurisdictional claims in …: 2021.
(16) Olanrewaju, O. I.; Enegbuma, W. I.; Donn, M.; Chileshe, N. Building information modelling and green building certification systems: A systematic literature review and gap spotting. *Sustainable Cities and Society* **2022**, *81*, 103865. DOI: https://doi.org/10.1016/j.scs.2022.103865. European Construction Technology Platform. *Horizon Europe 2022-2027, Digital Built Environment Committee, Position Paper*; 2022.
(17) Okakpu, A.; Ghaffarianhoseini, A.; Tookey, J.; Haar, J.; Ghaffarianhoseini, A.; Rehman, A. U. Risk factors that influence adoption of Building Information Modelling (BIM) for refurbishment of complex building projects: Stakeholders perceptions. *International Journal of Construction Management* **2022**, *22* (13), 2446-2458.
(18) Deng, X.; Lu, K. Multi-level assessment for embodied carbon of buildings using multi-source industry foundation classes. *Journal of Building Engineering* **2023**, *72*, 106705. Kim, K. P. Chapter 13 - BIM-Enabled Sustainable Housing Refurbishment—LCA Case Study. In *Sustainable Construction Technologies*, Tam, V. W. Y., Le, K. N. Eds.; Butterworth-Heinemann, 2019; pp 349-394.
(19) EPBD. Revised Energy Performance of Buildings Directive. 2024; pp pp 9-10.
(20) EU. Construction - Building Information Modelling. 2023.
(21) Charef, R.; Emmitt, S.; Alaka, H.; Fouchal, F. Building Information Modelling adoption in the European Union: An overview. *Journal of Building Engineering* **2019**, *25*, 100777. DOI: https://doi.org/10.1016/j.jobe.2019.100777.
(22) Green Alliance. *Less in, More out. Using resource efficiency to cut carbon and benefit the economy*; 2018.
(23) BCG. *Boston Consulting Group. Digital in Engineering and Design: The Transformative Power of Building Information Modeling*; 2016. https://www.bcg.com/publications/2016/engineered-products-infrastructure-digital-transformative-power-building-information-modeling.
(24) ACE, A. C. o. E. *The Architectural Profession in Europe 2020: A sectoral study*; 2020. DOI: https://www.ace-cae.eu/fileadmin/user_upload/2020ACESECTORSTUDY.pdf
(25) One Click LCA. *Construction Carbon Regulations in Europe*; 2022.
(26) London Assembly. *Whole Life-Cycle Carbon Assessments guidance*. 2024. https://www.london.gov.uk/programmes-strategies/planning/implementing-london-plan/london-plan-guidance/whole-life-cycle-carbon-assessments-guidance (accessed.
(27) UK Gov't. Government construction strategy 2011 2015. UK Government, Ed.; 2011.
(28) Boverket. *Limit values for climate impact from buildings*; 2023.
(29) Storenso.com. *Good for wood: new embodied carbon regulations*. 2022. https://www.storaenso.com/en/newsroom/news/2022/1/good-for-wood-new-embodied-carbon-regulations (accessed.
(30) Burohappold. The Netherlands: Regulating the environmental performance of buildings, taking a whole-life cycle approach. **2023**.
(31) storaenso.com. *French laws are decarbonising the building sector*. 2023. https://www.storaenso.com/en/newsroom/news/2023/9/re2020 (accessed. Ministere de la Transition Ecologique. https://www.ecologie.gouv.fr/sites/default/files/guide_re2020_version_janvier_2024.pdf. 2024.
(32) Dutch Environmental Database. Guide to environmental performance calculations. MileauDatabase, Ed.; 2020. Knowledge Hub. *The Netherlands: Regulating the environmental performance of buildings, taking a whole-life cycle approach*. 2023. https://knowledge-hub.circle-economy.com/AfricanCAT/article/22918?n=The-Netherlands-Regulating-the-environmental-performance-of-buildings%2C-taking-a-whole-life-cycle-approach (accessed 23/11/23).

(33) Autodesk Revit. *Inside Look at 12 Projects Winning With BIM - Perkins + Will Architects,*; autodesk.co.uk, Undated. DOI: https://damassets.autodesk.net/content/dam/autodesk/www/solutions/bim/docs/adsk-bim-excellence-ebook.pdf.
(34) Eastman, C.; Teicholz, P.; Sacks, R.; Liston, K. *BIM Handbook - A Guide to Building Information Modelling*; John Wiley & Sons, 2011.
(35) Foster & Partners. Innovation in Design, Presentation by Doretta Bevilacqua Gilkes, 24 May 2023. 2023.
(36) Wong, J. K. W.; Zhou, J. Enhancing environmental sustainability over building life cycles through green BIM: A review. *Automation in Construction* **2015**, *57*, 156-165. DOI: https://doi.org/10.1016/j.autcon.2015.06.003.
(37) Chong, H.-Y.; Lee, C.-Y.; Wang, X. A mixed review of the adoption of Building Information Modelling (BIM) for sustainability. *Journal of Cleaner Production* **2017**, *142*, 4114-4126. DOI: https://doi.org/10.1016/j.jclepro.2016.09.222.
(38) Nast, A.; Koch, C. BIM adoption in small-scale infrastructure projects–investigation on the German railway sector. In *ECPPM 2022-eWork and eBusiness in Architecture, Engineering and Construction 2022*, CRC Press, 2023; pp 695-702.
(39) NBS. *NBS 2023 Digital Construction Report*; 2023. https://www.thenbs.com/digital-construction-report-2023/.
(40) Rodriguez, B. X.; Huang, M.; Lee, H. W.; Simonen, K.; Ditto, J. Mechanical, electrical, plumbing and tenant improvements over the building lifetime: Estimating material quantities and embodied carbon for climate change mitigation. *Energy and Buildings* **2020**, *226*, 110324.
(41) Veselka, J.; Nehasilová, M.; Dvořáková, K.; Ryklová, P.; Volf, M.; Růžička, J.; Lupíšek, A. Recommendations for Developing a BIM for the Purpose of LCA in Green Building Certifications. *Sustainability* **2020**, *12* (15), 6151.
(42) Nordic Architects Letter. An Open Letter to Autodesk, by AiN, Association of Consulting Architects in Norway; ATL, The Association of Finnish Architects' Offices, Finland; Danish Association of Architectural firms; SAMARK, The Association of Architectural Firms in Iceland. 2022.
(43) Farmer. *Modernise or Die: Farmer Review of the UK Construction Labour Model*; 2016. https://www.constructionleadershipcouncil.co.uk/wp-content/uploads/2016/10/Farmer-Review.pdf.
(44) Eberhardt, L. C. M.; Birgisdottir, H.; Birkved, M. Potential of Circular Economy in Sustainable Buildings. *IOP Conference Series: Materials Science and Engineering* **2019**, *471* (9), 092051. DOI: 10.1088/1757-899X/471/9/092051. Fisher, P., Bennetts Associates,. Tilhill Forest Market Report Launch. **2023**. Huang, B.; Zhao, F.; Fishman, T.; Chen, W.-Q.; Heeren, N.; Hertwich, E. G. Building Material Use and Associated Environmental Impacts in China 2000–2015. *Environmental Science & Technology* **2018**, *52* (23), 14006-14014. DOI: 10.1021/acs.est.8b04104.
(45) CEMBUREAU. *Cement, Concrete & the Circular Economy*; 2016. https://circulareconomy.europa.eu/platform/sites/default/files/cement_concrete_the_circular_economy.pdf.
(46) CEMBUREAU. *Road Map to 2050: viewed 17.2.23*. 2023. https://lowcarboneconomy.cembureau.eu/carbon-neutrality/our-2050-roadmap-the-5c-approach-clinker/ (accessed.
(47) Segura, I. P.; Ranjbar, N.; Damø, A. J.; Jensen, L. S.; Canut, M.; Jensen, P. A. A review: Alkali-activated cement and concrete production technologies available in the industry. *Heliyon* **2023**.
(48) Greenspec.co.uk. *Green Building Design: Crosslam timber / CLT- Fire resistance and rating*. 2024. https://www.greenspec.co.uk/building-design/crosslam-timber-fire-resistance-and-rating/ (accessed Viewed 24.9.24.
(49) Triods Bank. *Triodos Bank remoountable timber-framed office*. 2024. https://www.dezeen.com/2021/02/21/triodos-bank-remountable-office-rau-architects-ex-interiors/ (accessed Viewed 24.9.24.

(50) White Arkitekter. White Arkitekter completes Gothenburg's first wooden office building. **2021**.

(51) Waugh Thistleton. *The Black and White Building, 21st Century Timber*. 2022. https://waughthistleton.com/black-white-building/ (accessed.

(52) Iacovidou, E.; Purnell, P. Mining the physical infrastructure: Opportunities, barriers and interventions in promoting structural components reuse. *Science of The Total Environment* **2016**, *557-558*, 791-807. DOI: https://doi.org/10.1016/j.scitotenv.2016.03.098.

(53) Nemry & Uihlein. *Environmental Improvement Potentials of Residential Buildings*; European Commission Joint Research Centre, Institute for Prospective Technological Studies, 2008. https://publications.jrc.ec.europa.eu/repository/bitstream/JRC46667/reqno_jrc46667_jrc46667%5B1%5D%5B1%5D.pdf.pdfDOI: 10.2791/38942.

(54) Rasmussen, F. N.; Ganassali, S.; Zimmermann, R. K.; Lavagna, M.; Campioli, A.; Birgisdóttir, H. LCA benchmarks for residential buildings in Northern Italy and Denmark–learnings from comparing two different contexts. *Building Research & Information* **2019**, *47* (7), 833-849.

(55) Wiik, M. R. K.; Selvig, E.; Fuglseth, M.; Resch, E.; Lausselet, C.; Andresen, I.; Brattebø, H.; Hahn, U. GHG emission requirements and benchmark values for Norwegian buildings. *Earth Environmental Science,* **2020**.

(56) UKGBC. *UK Green Building Council. Net Zero Whole Life Carbon Roadmap: Technical Report*; 2021. https://www.ukgbc.org/wp-content/uploads/2021/11/UKGBC-Whole-Life-Carbon-Roadmap-Technical-Report.pdf.

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