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An open building information modelling based co-simulation architecture to model building energy and environmental life cycle assessment: A case study on two buildings in the United Kingdom and Luxembourg

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ABSTRACT

Given the complexity and interconnection of different aspects involved in building evaluation, one of the most relevant, and challenging, research topics is the integration of different domain models (such as thermal comfort, indoor environmental quality and occupant comfort) to effectively describe and inform improvement strategies for the behaviour and performance of a building and building stock. Currently, this problem is unsolved with only one study attempting to integrate building energy simulation and life cycle assessments (separately, both practices are utilised to facilitate the design and management of buildings, traditionally consultancies offer building energy simulation services – most commonly for regulatory purposes – and more recently life cycle impact assessments), whilst no work has attempted this integration in a dynamic manner. This study addresses this gap by developing a dynamic, open building information modelling based co-simulation architecture. This architecture is the first to tightly couple and integrate EnergyPlus and Brightway2, in a way that does not rely upon heuristics or simplified tools. Furthermore, it is the first building energy simulation and life cycle assessment co-simulation to enable time-differentiated (dynamic) results and the first to be enabled only by open technologies. The architecture has been validated against two case-study non-domestic buildings located in the United Kingdom and Luxembourg, demonstrating its applicability to the construction and operational life cycle phases of buildings. The work presented in this paper has shown how a time-differentiated co-simulation approach across energy and lifecycle domains enables a more holistic analysis of whole buildings with greater accuracy and granularity.

1. Introduction

Given the complex interdependencies of the different aspects that impact upon a buildings' performance evaluation, to effectively and holistically describe the behaviour of buildings and building stocks, the integration of different domain models (such as thermal comfort, indoor environmental quality, occupant satisfaction, acoustic and visual comfort, glare prevention, aesthetics, etc.) is needed [1]. This integration of different domain models is possible via an emerging technique, entitled co-simulation. In a co-simulation, coupled simulations or systems are integrated to enable a "global" simulation [2].

More specifically, also (but not only) owing to the decrease in operational stage environmental impacts in high performance buildings [3], the building research community has heightened interest in the life cycle performances of such structures [3], which can be evaluated using the well-known life cycle assessment (LCA) methodology. However, the full potential for incorporating the lifetime effects of building construction and operation into the workflow is still untapped, with the majority of previous research either dealing with building energy simulations or LCA independently [4], providing no holistic view of the two in conjunction.

Therefore, this study takes the view that it is necessary to advance current simulation tools by developing co-simulation approaches that can model all the steps in the life cycle of a building, by integrating two previously disconnected methodologies, thus paving the way by

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Nomenclature

Abbreviations
Building Energy Simulation BES
Building Energy Model BEM
Life Cycle Assessment LCA
Building Information Modelling BIM
Industry Foundation Class IFC
Common Data Environment CDE
EnergyPlus E+
Brightway2 BW2
Open Studio/Application/Model OS/OSA/OSM
Cardiff University Sustainability Platform CUSP
Global Warming Potential GWP

Notations/Symbols and Units
Climate Change Impact unit - kgCO2eq

empowering building assessment through construction and operational phases. This study aims to fill this gap by addressing the lack of tightly coupled building co-simulation approaches – dynamic or otherwise - integrating Building Energy Simulation (BES) and LCA, through the development and validation of a co-simulation approach. Towards this aim, this study has investigated the following research question: *How can the tight integration of an energy simulation and life cycle assessment aid the design and management of buildings?*

To address this research question, this study has developed an open building information modelling (BIM) based co-simulation architecture, this has been implemented and then validated on two case study buildings. This validation will demonstrate the value that can be gained for building designers and managers, from time-differentiated (dynamic) LCA results from co-simulation of whole building energy simulation and LCA. The two case study buildings – located in the UK and Luxembourg – have been co-simulated within the developed architecture. For each building, three "scenarios" have been explored, encompassing both the construction and operational phases of a building's lifecycle.

In the remainder of this study, Section 2 presents background information necessary to this study. Section 2 further highlights the associated interoperability challenges around BIM and other relevant formats or schemas (for BES & LCA). In section 3, a systematic review is presented – following the PRISMA protocol – on the state of the art in co-simulation studies in the building domain.

Section 4 presents the methodology followed by this study. The open BIM based co-simulation architecture is presented in Section 5. This architecture is then validated in Section 6, in which two case study buildings are co-simulated and their respective results presented. Section 7 provides a discussion prior to Section 8 concluding this study.

Finally, to emphasise the novelty and conclude this introduction, this study has developed and validated an open BIM based co-simulation architecture for BES and LCA, applicable to whole buildings across both construction and operational phases. It is the first to; tightly-integrate E+ and BW2 and to integrate LCA and a nationally (UK) approved software program for BES [5]. This integration has allowed this research to maintain a dynamic foreground inventory for electricity, heating and water.

Regarding practical implications, this study has developed a clear and repeatable methodology for the co-simulation of BES and LCA - making a step forward in the co-simulation state of the art – which will enable and encourage further works in the co-simulation area. For industry professionals, this study presents a guide to provide time-differentiated/dynamic LCA results from BIM, addressing the demand to move beyond static LCA data, whilst simultaneously reducing time demands and cost. This architecture represents a streamlined process that may be used to investigate various scenarios to reach forecasted environmental targets. Whilst validated against buildings in the United Kingdom and Luxembourg, pursuing environmental agendas and targets is a global issue and so, this study seeks to provide an architecture that may be used by researchers, designers and managers and policy makers to reach/investigate their targets.

2. Background information

In the following sub-sections, background information is presented on the following topics; BES, BIM interoperability and LCA. BES' are conducted both to assist the designer and to fulfil building compliance processes. These digital energy simulations are conducted outside of the BIM framework which the construction industry is shifting towards and so this study explores the research into connecting BIM and BES approaches and their interoperability challenges. LCA, is a widely used methodology for the calculation of the impacts generated and the resources consumed by human activities – in this study, a building - and so this concept is introduced here. Elements in this section are widely accepted and are well-studied concepts and so, do not form back of the systematic review conducted in Section 3.

2.1. Building energy simulation

Building energy simulation (BES), building energy modelling, building thermal modelling, and building performance simulation are all terms to describe the process of creating a digital model of a building and performing a simulation in a chosen energy simulation program.

BES software has been in use since the 1960's [6], however, in its present state, has not been integrated sufficiently into the building planning and design processes. Therefore during early design stages, energy efficient design strategies, typically are not well implemented [7].

This lack of systematic BES usage, coupled with the lack of continuous information flow possible in digital modelling (where information in the building energy model (BEM) has to be manually re-inserted, which is considered labour intensive, therefore time consuming and costly) has led to the recent development of BIM to BES approaches [7–9].

Geometry creation is considered the most time-consuming task in energy modelling practices, beyond geometry, the assignment of key inputs (for example; constructions, internal gains and schedules) are also considered time-consuming [8]. BIM to BEM approaches addressing this problem differ in their levels of automation and information integrity, though no studies to date have successfully achieved fully automatic lossless application of BIM to BEM.

For instance, O'Donnel et al. generated a BEM model using the Lawrence Berkeley National Laboratory semi-automated tool [9]. The tool consists of three elements, the Space Boundary Tool (SBT-1), an Internal Load Generation Tool and Simergy for EnergyPlus. A key limitation in this study was that IFC (Industry Foundation Class) based exports of building geometry do not include explicit material definitions needed for BES processes. The authors found the following benefits from this semi-automated process; 1) the time and cost required to develop a whole building energy simulation model is reduced, 2) the process enables the ability to generate design alternatives rapidly, 3) the process improves the accuracy of BES' 4) the process outputs building models that exhibit significantly lower energy consumption than those typically produced from the traditional design process.

Of the benefits discussed, 1 and 2 can be generalised as *efficiency increases* whilst 3 and 4 are *technical improvements*. Other studies highlight *efficiency increases* as outcomes of BIM to BEM, where the replicability and re-usability of information enables more time to be assigned to performance analysis and design optimisation [10,11].

Nonetheless, the processing and exchanging of BIM to BEM remains a major challenge [8]. The studies and approaches described thus far are difficult for practitioners to use as they require the knowledge and use of many software tools. Elagiry surmises in a review study that the current barriers to full BIM to BEM implementation [8] lie within two aspects; 1) IFC generation – is challenging with respect to accuracy, consistency and manual correction and 2) Energy data enrichment – is necessary with respect to; site, geometry, constructions, internal gains, systems, spaces controls, energy costs and renewables.

Similarly, Alsharif provides an extensive review of BIM to BEM applications and investigates two case studies in which the BIM originates from two different proprietary software tools; Revit and IES VE [12]. The study finds that both case studies present interoperability challenges, namely:

- Location related parameters: information (can or is) in schemas by authoring tools, but not retrieved by simulation software.
- Geometry related discrepancies.
- Material properties: information can technically be stored in data schemas, however, there is no capacity for authoring tools or simulation tools to exchange these.
- Building systems: there is limited ability within the interoperability of heating, ventilation and air conditioning systems.
- Building operation: similar to location parameters, information may be stored but not exported to other tools.

Alsharif concludes that BIM-based BEM automation is essential to drive forward the design and construction industries [12]. Aligning the two studies by Eligary and Alsharif [8,12], two main interoperability challenges are recognised at present: 1) IFC Geometry Generation – with discrepancies in geometry requiring manual correction and 2) Enrichment – where data required is either; unavailable, untranslatable or unretrievable including; site location, material properties, internal gains, systems and controls and finally, building operation.

2.2. BIM and interoperability

BIM or building information modelling, represents buildings in a graphical three-dimensional model, covering information on a building including; geometry, properties, names and the functional peculiarities of components [13]. The construction industry is currently shifting towards BIM, away from traditional 2D drawing based information system [10]. Several papers have used BIM as a basis for “BIM to BEM” approaches [14]. Other papers utilise BIM as a basis for LCA [15], as described in the review by Teng et al. [16]. In both cases, the BIM forms the initial input requirement. Separately, studies have described IFC conversion to gbXML [17] in attempts to automation or semi automate this transformation.

Several approved software programs/calculation methodologies to calculate energy performance are available, though many of these share the same calculation engine. Commonly approved energy simulation approaches include: TAS, ApacheSim, E+ and SBEM [5]. Of these four software programs, SBEM is the only “Simplified Building Energy Modelling” tool, whilst the remaining three are “Dynamic Simulation Modelling” tools. Of these tools, only E+ is “free” and “open-source”, whilst the remaining tools are proprietary with closed formats. For this reason, E+ is the preferred tool within these works. Similarly, E+ is specifically a calculation engine. For energy modellers, a graphical user interface (GUI) or frontend is preferred, especially when modelling realistic or complex buildings. The de-facto frontend for E+ is the Open Studio Application (OSA). E+ utilises a .idf as its native file format, whilst OSA utilises a .osm, which is later translated into a .idf at simulation time.

2.3. Life cycle assessment

Environmental LCA is a well-known and widely used methodology for the calculation of the impacts generated and the resources consumed by human activities (products, services, processes, policies) across their entire lifecycle. It is regulated by the ISO norms of the 14000 series (14040–14075), which outline the general framework for conducting an LCA study without providing specific operational guidelines on how to deal precisely with every decisional context.

A key element in LCA studies is the definition of the functional unit. The purpose of the functional unit is to provide a reference unit of the product or service studied and allow comparability between different products or services that can deliver the same reference function. If the study addresses the same performance or function, the performance can be reasonably compared [18].

The advantage of LCA is that, since the method takes a lifecycle-based perspective, it avoids burden shifting, where the improvements brought to a certain phase of the lifecycle can cause the reduction of the impacts caused by that phase but generate an increase of the impacts in a different phase. Moreover, since when comparing alternatives it is very difficult to have one that dominates the others on every impact criterion, LCA is very useful to perform trade-off analysis.

In the building community LCA is a widely accepted approach [3] and countless studies have been carried out on buildings and building components, from the single building to districts or larger building stocks [19,20]. When a single building is taken into account, LCA can be used to inform the design of the building in the early stage [21] to influence its construction, as well as in the operational phase, to select the best strategy for building operation [22].

The most commonly used professional LCA software packages include SimaPro [23], openLCA [24], GaBi [25], or Umberto [26]. Advanced use of LCA software through programming is possible using the stand-alone programming framework BW2 [27], which has been recently enriched with a more user-friendly interface called Activity Browser [28]. Regardless of the software package used, an important element in conducting LCA is background data - with good quality data being required - typically practitioners use life cycle inventory databases to access background data, with the ecoinvent database being the largest transparent LCI database worldwide [29].

A comprehensive review of different applications of LCA in the building sector and future challenges and research directions in this field is provided by Fnais et al., [30]. Some of the challenges and at the same time most promising research directions are related to the potential of BIM [16] and digital twinning [31] in providing more accurate and highly specific data to perform LCA. When co-simulation approaches are applied in building modelling in conjunction with data collection via sensors, a better material or occupancy characterization is rendered possible. This allows one to perform simulations using specific simulation models to cover different aspects of the building-occupant interaction and integrate their results in the LCA [32].

3. State of the art in Co-simulation within the building domain

In the following sub-sections, the concept of co-simulation is introduced in Section 3.1, before the systematic state of the art review of co-simulation within the building domain is presented in Section 3.2, existing efforts in co-simulation are examined and areas in which this work advances the state of the art are identified.

The state of the art review in Section 3.2 has been conducted following the PRISMA protocol [33]. The search was conducted on a range between March 2017 up until January 2023, this date range was used as other studies cover the state of the art in co-simulation up until this period [2]. This review considered only journal articles and review articles, records were retrieved from Semantic Scholar at the beginning of 2023 using the search string: *(ALL = (co-simulation)) AND ALL = (buildings)*. An overview of this process is illustrated in Fig. 1, adapted from the PRISMA 2020 statement [33].

An initial search using the previously mentioned, search string returned 392 records. This review only considered journal articles and

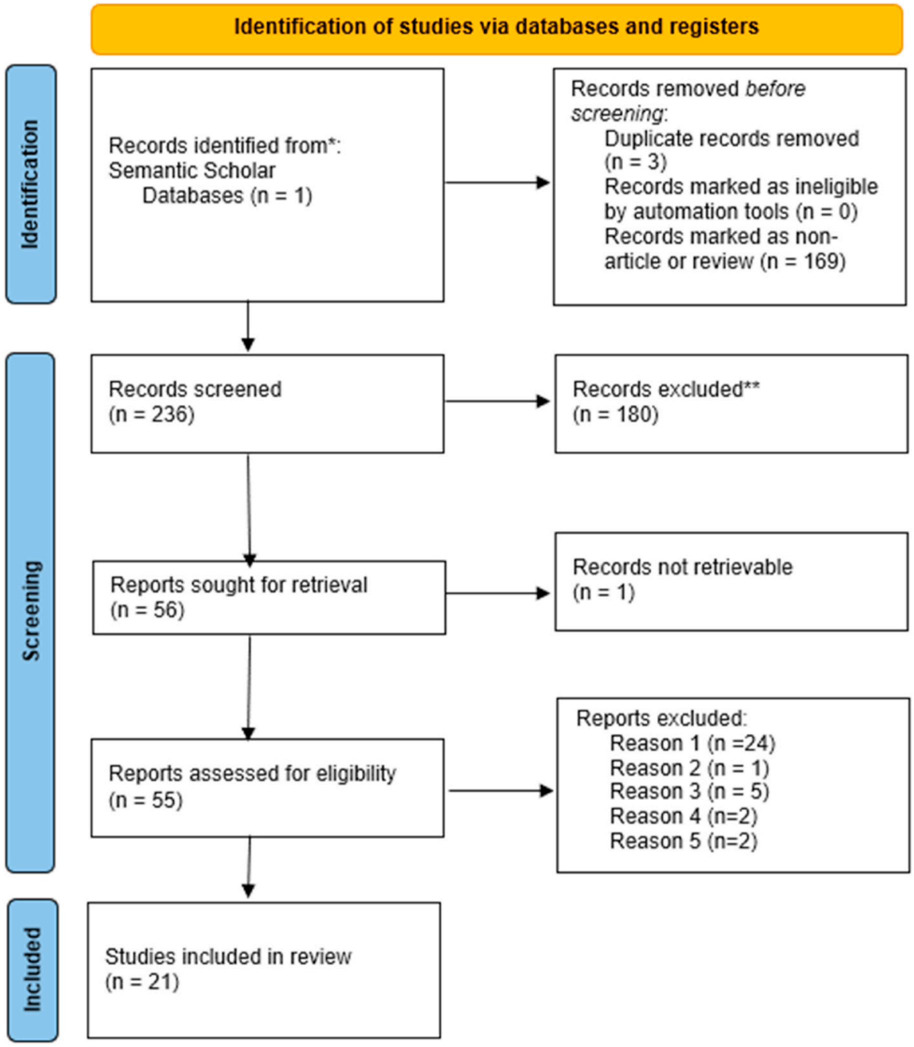

Fig. 1. Systematic review methodology (based on PRISMA 2020 statement flow diagram [33]).

reviews, and so, 169 records were removed leaving only 223 articles and 16 reviews for a total of 239, 3 records were marked as duplicates and removed leaving 236.

The abstracts of the remaining 236 records were considered for screening, based on this screening statement: studies that develop and apply approaches coupling different building domain models – co-simulation - to describe the interaction between different building sub-systems, which left 56 records. These 56 records were sought for retrieval with only 1 record marked as non-retrievable.

The remaining 55 records were retrieved and considered before finally excluding 34 records leaving 21 to be included in the state-of-the-art review. There were 5 exclusion criteria for the final inclusion process: 1. Study lacks domain-to-domain coupling or couples' models and systems within a domain, 2. Study does not develop and apply a co-simulation approach, 3. Approach does not push forward the state of the art within that domain(s) in describing the interaction between building sub-systems, 4. Duplicated or highly similar work not screened prior and 5. Study only compares a previously developed co-simulation approach against approaches applied traditionally.

3.1. Introduction to Co-simulation

Co-simulation is applied in different fields, although the communication and information sharing among them has not been efficient so far, as highlighted by Gomes et al. [2], who realised an inter sector survey spanning applications from 2011 to 2016. The fields where co-simulation approaches have been found are: Automotive; Electricity Production and Distribution; HVAC, Information and Communication (IC) and system-on-chip (SoC) Design, Maritime, and Robotics [2].

Co-simulation approaches are necessary to achieve innovative and optimal multi-disciplinary solutions deriving from the integration of partial solutions developed independently (to cover different aspects of the studied problem) [2]. In fact, in composite simulations where different aspects of the problem must be solved simultaneously, partial solution developed by different specialized single purpose tools (monolithic legacy tools) are difficult to integrate [1]. Co-simulation has emerged as a solution to these challenges and enables global simulation of a system that integrates various simulators. Each simulator is a black box mock-up of a constituent system and may be managed separately, even by different teams.

According to Trčka [34], the advantages of co-simulation are: (a) the possibilities in the combination of simulation and approaches using tools suited to the sub-system modelled, (b) the ability to achieve rapid testing of software prototypes, (c) the facilitation of work distribution among parallel teams, including the option to retain closed file formats and APIs, and (d) the access to multi-scale simulations which address the interactions between different sub systems (where each are modelled with an appropriate level-of-detail).

In building simulation, co-simulation is usually used to couple sub models that exchange simulation data during runtime and describe different aspects of the building envelope and its interaction with occupants (namely, thermal models, airflow models, daylighting models etc.) [1].

Various strategies and techniques exist to implement the coupling of the different calculation modules in a co-simulation approach [1]. A first differentiation is between sequential and bi-directional coupling strategies. In the former case, the simulators transfer information to one another sequentially (the results of one simulator are fed to the other), with no feedback, while feedback loops are possible in the latter case. Furthermore, bi-directional coupling can be performed either in a strong coupling mode or in a loose coupling mode. In the loose coupling case, each model uses the results of the previous model at every time step, while in the strong coupling case the solvers need to reach predefined convergence criteria to complete each step and move to the next one. As far as the coupling techniques are concerned, Taveres-Cachat et al. [1] distinguishes between three possibilities. The first, one-to-one coupling, concerns the direct connection between two simulators [35]. The second, more flexible solution, relies on middleware. In this case several simulation programs can be coupled, instead of having a direct link between only two simulators. The middleware acts as an orchestrator of the simulation process; it manages data exchange between the simulators and facilitates post-processing. Known examples of middleware for co-simulation are the building control virtual test bed (BCVTB) [36] and RabbitMQ [37,38]. The third technique consists in using a so-called standard interface approach, which works via direct coupling with any software tool equipped with the same interface. The functional mock-up interface (FMI) is a widely used standard in the building performance simulation domain for software coupling. While it is based on the Building Control Virtual Test Bed, it is in fact an interface standard that allows co-simulating two or more simulation programs in a co-simulation environment [39]. This approach provides a more streamlined method versus the Building Control Virtual Test Bed and supports model exchange and co-simulation using XML, C-code and C-header files [40]. Both approaches support hardware-in-the-loop (simulation, which is useful in designing controls for advanced building envelopes and can be used in parallel to co-simulation schemes.

Another distinction that can be made is between internal coupling and external coupling [41]. For example, in the case of integration of CFD and BES, in internal coupling a CFD code is developed within a BES environment [42,43]. In external coupling, existing tools work in parallel and exchange data on a time-step basis [44].

In the building domain, one advantage of co-simulation is related to the possibility to factor in occupant behaviour and occupant related triggers [40]. It is in fact estimated that occupants' behaviour can be responsible for a high share of the performance gap in buildings, heavily influencing the final energy use [45,46]. Some studies have coupled a separate occupant behaviour software module to a BES program, using co-simulation [40].

Furthermore, co-simulation is the only viable solution when subsystem trade-offs must be evaluated [1]. This is the case, for example, in scenarios that interlink energy performance, user requirements and indoor environmental quality performances. Co-simulation can be used in real-time simulations of advanced building envelopes, since many of these systems are characterized by dynamic behaviours [47]. In the building domain, E+ and TRNSYS are the most widely used tools in this category. Recently, machine learning techniques – such as predictive control and deep reinforcement learning linked to parametric generation - have been adopted in this field [48–50].

Although the interest towards co-simulation approaches is growing fast (especially since 2013 [47]), there are still existing hurdles to their systematic application. Taveres-Cachat et al. [1] identifies them as mainly two interrelated issues: standardization gap and a knowledge gap. The former stems from the lack of interoperability between different BES software, mostly since BES tools have different levels of detail and different ways to process inputs. This brings to the tightly related issue of the standardization gap. Co-simulation is currently mostly carried out by experienced BES users, but their application is not widely pursued, due to the lack of accessible shared documentation, the need for strong programming skills and a deep knowledge of the governing laws of the phenomena modelled in BES tools.

In the buildings sector, some existing BES tools are compatible with architectural software and interoperable with BIM, from which inputs can be imported through IFC. Parametric scripting platforms such as Grasshopper in the Rhinoceros 3D modelling environment have become very popular in architecture and offer several opportunities for the integration of loosely coupled co-simulation approaches. In particular, the Ladybug Tools [51] support performance-based designs. Beyond this, Grasshopper allows for structural engineering analysis and optimisation approaches. However, with regards to co-simulation, this information could be further integrated into a multi-domain workflow spanning the entire development of a building envelop [1]. In this way, the information processed through co-simulation can be directly linked to costs or greenhouse gases (GHGs) emissions from materials and building operational phases [52].

3.2. Systematic state of art review of Co-simulation in the building domain

The studies discussed in this section are presented in sub-sections organised by domain-to-domain classifications. Within each classification, studies are presented chronologically concluding with the latest studies.

3.2.1. Energy and climate

Since 2017 the first study to couple energy and indoor climate domains was Ferroukhi et al. the authors developed a BES and heat, air and moisture co-simulation approach [53]. Co-simulation was enabled through Matlab and the simulation tools coupled were TRNSYS (a building energy simulation software) and COMSOL (a multiphysics simulation software). The thermophysical properties of walls were analysed and the approach validated by results comparing predicted and measured data. Conversely, the first study to couple building energy and urban climate domains was Morakinyo, in this study, E+ and ENVI-met (a micro-climatological and computational fluid dynamics model) were integrated to study temperature and electricity reduction from green roof configurations in various urban climates and configurations [54].

In 2018, Benzaama et al. developed a co-simulation approach coupling TRNSYS and FLUENT (a computational fluid dynamics software) to simulate both; the temperature of air and surfaces in a space and the dynamic behaviour of indoor air in that space [55]. Also coupling TRNSYS and FLUENT, Shen et al. developed an approach in 2019, coupling building energy and neighbourhood level computational fluid dynamics to assess the impact of external convective heat transfer on building thermal performance, the approach utilised the BCVTB [56]. Lassandro and Turi again used E+ and ENVI-met as an interrelated tool to support decision making around heat wave mitigation, the tool was applied to the energy retrofit of building and urban area in Bari, Italy [57].

In 2019, Less et al. developed an approach co-simulating energy and ventilation domains, the authors investigated the application of smart ventilation controls on homes in California co-simulating E+ and CONTAM [58]. A similar study was conducted in 2020, O'Neill et al. investigated the energy and ventilation performance of a C02 based demand-controlled ventilation system. This study used the FMI to co-simulate E+ and CONTAM (an indoor air quality and ventilation software, with the study finding that the control strategy achieved “good” compliance against ASHRAE Standard 62.1 [59]. Underhill et al. also conducted a E+ and CONTAM co-simulation to quantify health and energy costs, again in relation to energy retrofit in a midrise multifamily building [60], the authors found that weatherization retrofits reduced energy consumption and outdoor emissions, though without ventilation/filtration, particulate matter concentrations were increased indoors.

Zhang and Gao investigated the effects of floor area ratio, surface area ratio and mean sky view factor of eight generic residential districts in 2021 using an E+ and ENVI-met co-simulation [61]. The study concluded that both the ratio factors were negatively correlated with heating and cooling loads, whilst the mean sky view factor was positively correlated. Abuseif et al. also used E+ and ENVI-met to study the effect of green roof configurations on indoor and outdoor temperatures alongside cooling demand, this study found that green roof performance had a greater performance on indoor temperature than outdoor [62].

Lou et al. coupled E+ with Radiance (a ray tracing, lighting simulation software) to study energy and daylight performance for air-conditioned atriums [63]. Results from Radiance were imported into E+ for evaluation, finding that for hot and humid climates, skylight coverage ratio must be controlled to avoid overheating.

In 2022, Kharbouch et al. used a co-simulation approach to evaluate the performance of an earth-to-air heat exchanger [64], the heat exchanger was modelled in Matlab and the BCVTB was used to exchange information with E+. The authors were able to validate the use of an earth-to-air heat exchanger through sensors installed in the building. Whilst the classification of domains in this study are debatable, the co-simulation can be said to couple energy and heat transfer and evaluates the performance of a building sub-system not representable within a single domain software tool. Another instance of this can be seen in Zhang et al. where the authors have coupled a dynamic heat transfer model with E+ to evaluate vertical green facades [65].

3.2.2. Energy and occupant behaviour/health

In 2017, Chen et al. developed an occupant behaviour and energy co-simulation and visualisation approach – coupling Occupant Simulator, obFMU and E+ to estimate the mutual effect between occupant behaviour and energy performance in buildings, beyond this the authors developed AnyLogic, a visualisation module enabling the communication of occupant behaviour energy effect with stakeholders [66]. With conceptual similarities but technical differences, in 2020, Yi developed another visualised co-simulation approach, considering adaptive human behaviour and dynamic building performance [67], in this approach, co-simulation was achieved through the BCVTB, interfacing E+ and Radiance, coupled with an agent-based model to describe occupant behaviour, visualisation was implemented through Grasshopper. In another study that pushed the state of the art one step forwards, Jia et al. coupled E+ with an agent-based model for occupant behaviour in a study comparing building performance with actual occupant behaviour information against a multi-based model. The study found that the agent-based model reported lower energy-consumption and may be used to plan or encourage energy conservation measures [68].

Mokhtari and Jahangir in 2020 presented the first study to couple building energy and human health domains, investigating the effect of building occupants on energy consumption and COVID-2019 infection [69]. Matlab is used as a communicator, whilst E+ provides energy consumption values and the infection of COVID-2019 is solved by a NSGA-II algorithm. The study concluded with findings of up to 56% reduction in infection and 32% reduction in energy consumption when an optimal population distribution was found. William et al. made a step forward in this area of work in 2022, developing a BES and computational fluid dynamics model to assess the reconfiguration of indoor spaces in response to COVID-2019, the study found that underfloor air distribution systems reduced the likelihood of infection and transmission [70].

3.2.3. Energy and acoustics

Ferrara et al. were the first (and only) authors to couple energy and acoustic domains in 2021, this study developed an approach that coupled sound insulation performance, energy performance and cost optimisation [71]. The approach was applied to the design of comfort-driven, nearly zero energy single family buildings, addressing the low sound insulation performance of traditional cost-optimised nearly zero energy buildings.

3.2.4. Energy and environmental life cycle

Cellura et al. authored the first (and only) study since 2017 coupling energy and the environmental life cycle domains, here, the authors developed a LCA tool applied to TRNSYS building models capable of performing LCA studies. The tool was validated against a case study simulation of a residential house in Italy [4]. Cellura et al. states that, when it comes to the integration of fully-fledged LCA with BES, studies are lacking and in most cases the components are used as distinct methodological approaches, not including the co-simulation of different tools or development of innovative instruments. In fact, they surmise that enhancing the potential to couple different domain models to effectively describe the interaction between different sections and parts of the building is key for the advancement in building related research.

3.2.5. Occupant behaviour and fire safety

In 2021 Shams Abadi et al. coupled occupant behaviour and fire safety domains by developing a BIM-based co-simulation of fire behaviour and occupant behaviour though an agent-based model [72], egress times were estimated through various construction sequencing scenarios and alongside time and cost, used as decision making criterion. The authors applied this approach to a three-storey high rise educational building in Montreal and evaluated the renovations construction plans.

3.3. Research gap

This review has identified that whilst developing approaches that enable the coupling of different domain models to effectively describe the interaction between different elements of the building is key for the advancement in building related research, studies fully integrating BES and LCA are lacking (in terms of substantial bodies of work and those with dynamic qualities) and in most cases are used as two distinct methodological approaches. Only one study has attempted to integrate building energy simulation (BES) and life cycle assessments (LCA), however to date no work has attempted this integration in a dynamic way [4]. Thus, this study has developed an open BIM based, time differentiated, co-simulation architecture which is presented in the following section. This architecture is the first to tightly couple E+ and Brightway2, in a way that does not rely upon heuristics or simplified tools. Furthermore, it is the first BES and LCA co-simulation architecture to enable time-differentiated (dynamic) LCA results and is also the first to be enabled only by open technologies (E+ and BW2).

4. Co-simulation architecture

This section will describe in detail, each element of the open BIM based co-simulation architecture developed in this study. Fig. 2 illustrates a use case diagram, illustrating how this architecture can be used by designers and managers. Fig. 3 illustrates the architecture of the open BIM based co-simulation architecture. In the following sections, arrows in Fig. 3 will be referred to as *processes*.

4.1. Component 0: BIM authoring tools

Component 0 in Fig. 3 encompasses, the conversion to IFC and BIM enrichment (process 0.1). This is a single process but is represented as two in Fig. 3 to illustrate that this element of the process is functional with a variety of BIM authoring tools. A prerequisite for this workflow is an IFC model of a building. In general, BIM authoring tools have the capability to export models into an IFC schema, and so exemplar authoring tools Revit and ArchiCAD are represented in Fig. 3, other BIM authoring tools capable of IFC export would be equally suitable.

This co-simulation architecture sets certain data requirements for input BIM's. BIM's are typically developed for non-BES purposes, rather

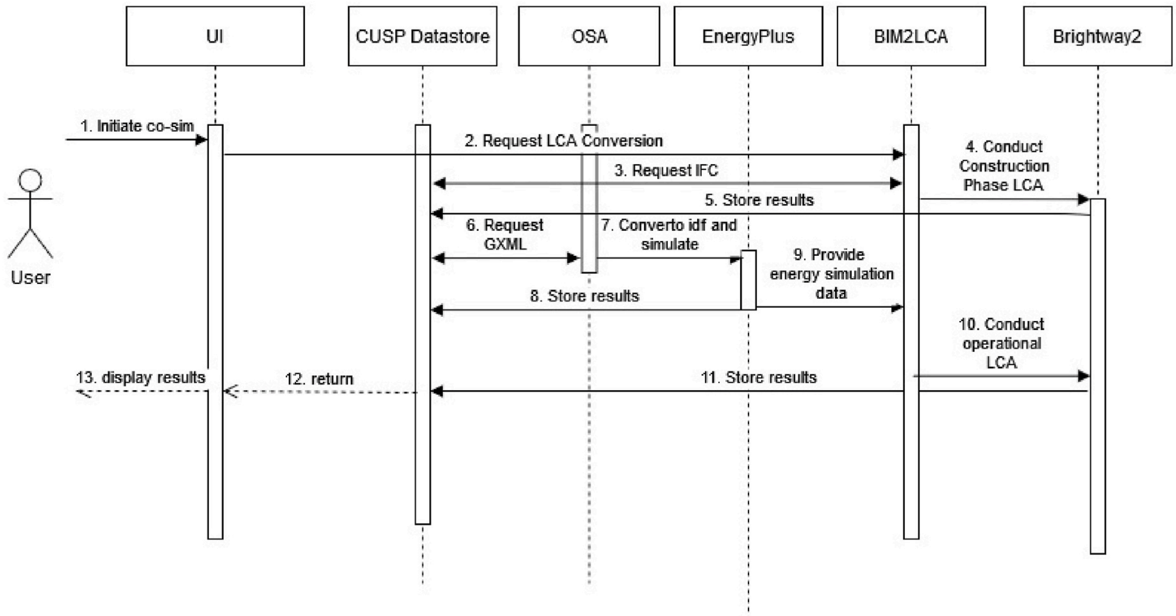

Fig. 2. Co-simulation use case diagram.

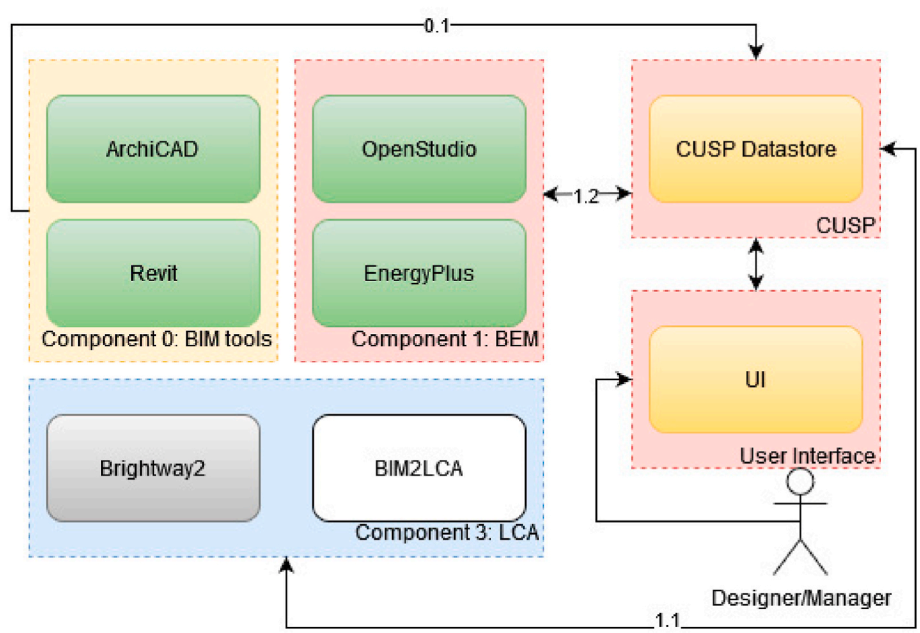

Fig. 3. Open BIM based co-simulation architecture.

their own, and so information required from a BES perspective is not contained within the BIM, as is in the case of the two case studies presented in section 5. Thus, before this architecture can be applied BIM's should contain a sufficient level of detail. These requirements are outlined below:

1. All spaces defined and types assigned to the spaces - For all rooms in the BIM a "space" is inserted, space types such as; corridor, closed-office, plantroom, WC etc are assigned
2. Definition of thermal zones - thermal zones may be defined to represent room(s) of interest or complex arrangements.
3. Define materials and assign constructions - material makeup for all constructions are assigned

Steps 1 and 2 are commonly completed in well specified BIMs produced currently. Step 3, however, may require additional enrichment beyond the standard norms. It should be highlighted that even though exports from some BIM authoring tool into IFC format do not necessarily create a perfect conversion of geometry from all elements, this architecture can overcome this issue through the definition of spaces.

This architecture elected to define these BIM requirements as a prerequisite to the co-simulation architecture. However, only Step 1 is necessary. Steps 2 and 3 could form part of the BES enrichment process in Component 1 – which does form part of the architecture – however, the authors elected to do so here for two reasons. In the context of the building design process, BES models are created at a later stage than the BIM. Typically, in BIM creation, spaces have already been defined in the BIM to fulfil functions such as floor plan legends. Similarly, BIM's inherently represent the properties of elements so materials and thermal zones are already defined. Therefore, it is logical to represent these steps here, rather than to duplicate or redo later.

4.2. Component 1: interoperability processing

4.2.1. BIM to BEM

The enriched BIM in IFC format is then exported into a model schema that can be imported by an energy simulation tool. An automated translation tool was developed and then used to translate an IFC file into either a Green Building XML file (gbXML) or a HBjson file (process 1.2).

4.2.2. BEM enrichment

The gbXML or HBjson is then imported (processes 1.2) into the user interface. Firstly, a weather file is fetched from an online service and this is linked to the imported gbXML/HBjson. At this stage, BEM enrichment is conducted via the UI presented in Fig. 4, the elements that are inputted are building services systems and internal loads.

4.3. Component 3: life cycle assessment

The enriched BIM in IFC format is also used to drive the LCA calculations (process 1.1). The BIM2LCA software tool developed for this architecture allows the parsing of the IFC file to extract material information for the different constructions in the building. In addition, this software tool contains a functionality to retain associations between activities (process that transform one or more materials into a different form i.e. mixing concrete) in a BW2 project [27] and material names.

Each of these materials are then in turn retrieved from ecoinvent 3.8 (packaged as part of BIM2LCA). BIM2LCA also contains a default list of methods from the Environmental Footprint 3.0 methodology. The Environmental Footprint methodology is an established framework developed since 2007 and is continuously maintained by the European Joint Research centre [73] which is summarised in Table 1, this table details the impact categories, indicators and units used within the method. This step is undertaken in this co-simulation architecture to provide an accepted set of categories and indicators; however, the user can personalize these associations and select new methods. BW2 is used as the LCA calculation framework to perform the calculations for the output from the BES (process 2.2). In Table 1, CTUh stands for

Table 1
Summary of EF3.0 method.

Impact category	Indicator	Unit
Water use	User deprivation potential	m^3 world eq. deprived
Photochemical oxidant formation: human health	Tropospheric ozone concentration increase	kg NMVOC eq
Particulate matter formation	Human health effects associated with exposure to PM2.5	Disease incidences
Material resources: metals/ minerals	Abiotic resource depletion	kg Sb eq
Land use	Soil quality index	Dimensionless
Human toxicity: non-carcinogenic	Comparative Toxic Unit for humans (CTUh)	CTUh
Human toxicity: carcinogenic	Comparative Toxic Unit for humans (CTUh)	CTUh
Eutrophication: terrestrial	Accumulated Exceedance (AE)	mol N eq
Eutrophication: freshwater	Accumulated Exceedance (AE)	kg P eq
Energy resources: Non renewable	Abiotic resource depletion – fossil fuels (ADP-fossil)	MJ
Climate change	Radiative forcing as Global Warming Potential (GWP100)	kg CO_2 eq

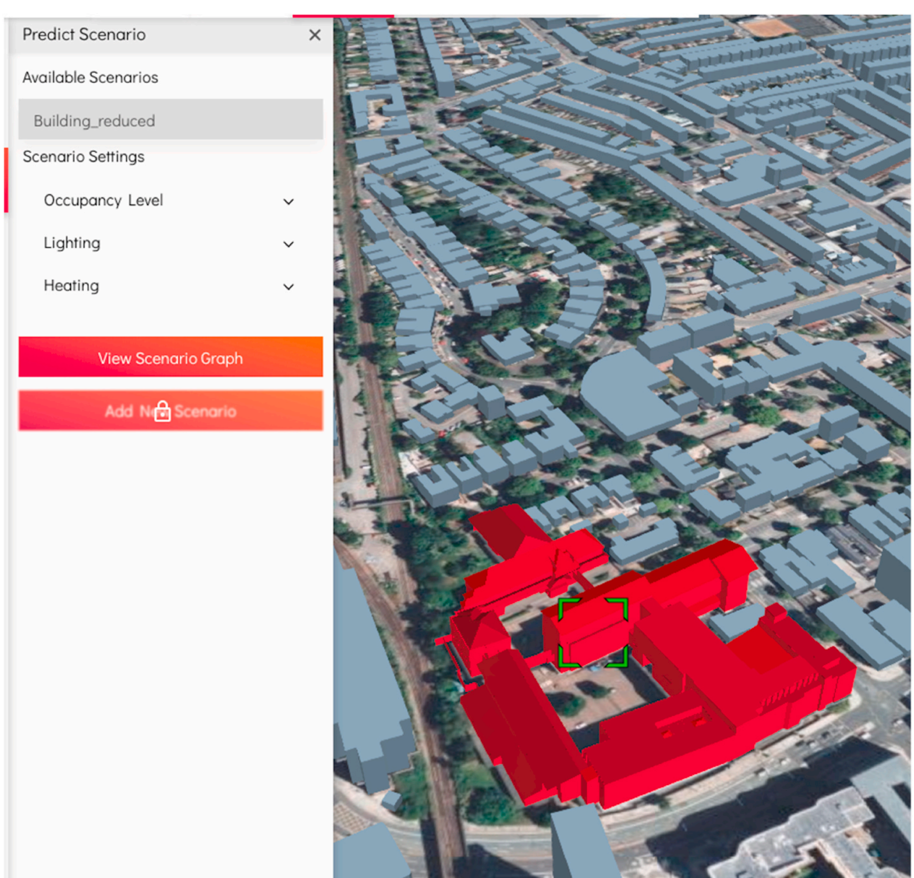

Fig. 4. User interface.

"comparative toxic unit for human toxicity" impacts, which expresses the estimated increase in morbidity (the number of disease cases) in the total human population per unit of mass of the chemical emitted. Water use is expressed in "World eq. deprived", which is the user deprivation potential (deprivation-weighted water consumption). It is calculated using the available water remaining (AWARE) method [74] which computes the volume of water available after human use and environmental requirements (a certain volume of water is necessary for the ecosystems survival) for each region.

The user can interact with the co-simulation via the User Interface. The interface allows the user to access the results of the simulation, make changes and execute new simulations in E+. The interface further enables the user to execute LCA functionality via BW2.

4.4. Co-simulation execution and output

At this point a simulation is conducted to generate an .idf which is sent to the CUSP semantic data store (process 1.2), along with the energy mix data. The BIM2LCA package then conducts the operational phase LCA before storing the results from the co-simulation in the CUSP data store. Finally, the results from co-simulation for both the construction and operational phases are displayed to the user.

With the co-simulation of whole-building BES and LCA, one can better inform the LCA with energy data that is time-differentiated. By adding this dimension in turn, this architecture is able to represent dynamicity in the operational phase of the building through time-differentiated LCA results. In the following sections case-study validations are presented which explore the time-differentiated results with examples.

4.5. Conclusion

This section has introduced and described each element of the co-simulation architecture. In summary, a given user can interact with the workflow presented here via the CUSP user interface. The interface enables the user to access both the BIM and associated functionality for both BES and LCA purposes (derived from E+ and BW2 respectively).

5. Case -study validations

The co-simulation architecture presented in Section 4 has been validated against two case study buildings: a university building in the UK and an office building in Luxembourg. The university building is one of several buildings forming part of Cardiff University's School of Engineering Campus. Located in the centre of Cardiff city with a floor area of 3728 m^2, this building is comprised of three occupiable floors, containing various room types (laboratories, offices, dining spaces and restrooms).

The office building in Luxembourg hosts the Luxembourg Institute of Science and Technology. Built more recently than UK building, this building - with a floor area of 9231 m^2 - is comprised of 5 occupiable floors, containing various open and closed office spaces.

The university model was originally authored in Revit, whilst the office model was originally authored in ArchiCad. Therefore, this workflow has been tested to be valid on both Revit and ArchiCad formats. Figs. 5 and 6 represent respectively the IFC models forming the basis for the university and office building case-studies. Figs. 7 and 8 detail the resulting spaces imported into OSA.

For each building, 3 scenarios have been co-simulated over an annual period:

1. Building_Base - "baseline" scenario with typical occupancy and operation
2. Building_reduced - with occupancy and operation reflecting the year 2020
3. Building_reduced 0 ht - per scenario 2 with further reduced heating load (where certain spaces have heating load reduced to zero assuming non-occupancy)

Regarding scenarios 2 and 3, this simulation applied occupancy and operational schedules derived from the year 2020. The year 2020 presented an abnormal operational period for buildings due to the COVID-19 pandemic, and so schedules for occupancy and operation are based on the Institute for Government COVID timeline in tantamount with the experience lived by the authors in their respective buildings [75].

These three scenarios have been explored with the purpose of analysing and quantifying the benefits of time-differentiated LCA results over traditional static results. By contrasting the results derived from the simulation of varying building operation this study aims to capture the resulting effects on environmental impacts and how designers and managers can use that data. The results from these scenarios will evidence how the integration of BES and LCA can aid the design and management of the two case study buildings.

Regarding electricity and heating consumption, the CUSP user interface enabled the execution of the LCA functionality via BW2, allowing for the integration of LCA results with a BES. Any changes made within the BES could then be injected back into the BIM. Thus, the LCA results were effectively integrated into the BIM, improving the comprehensive representation of the building's operational environmental impact.

5.1. Case study 1 – university building, Cardiff

For this case study, Fig. 9 displays the LCA results for the materials footprint and energy consumption of the university building model, for this validation the lifespan of the building was assumed to be 50 years. These results provide information on the environmental impact of the building and highlight areas for improvement. Impacts related to the building's material demand dominate most categories, including land use, water use, and impacts on human health and ecosystems. This highlights the importance of considering the materials used in building construction and their associated environmental impacts. However, the results also show that heating and electricity consumption become more relevant with regards to energy resources and climate change. This trade-off between material use and energy consumption highlights the need to consider the environmental impact of both building materials

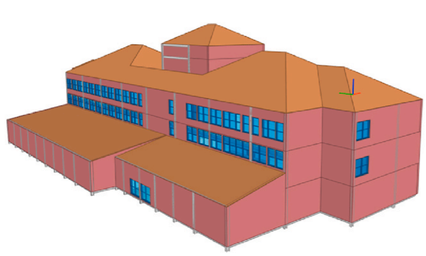

Fig. 5. IFC representation of the university building.

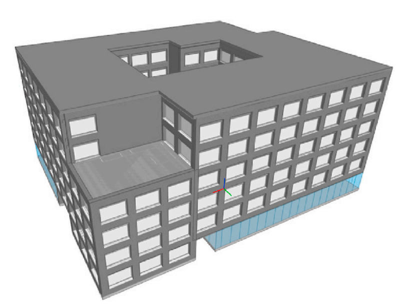

Fig. 6. IFC representation of the office building.

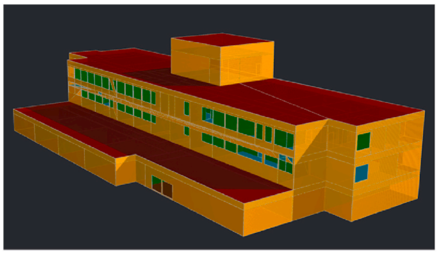

Fig. 7. University building imported spaces in OSA.

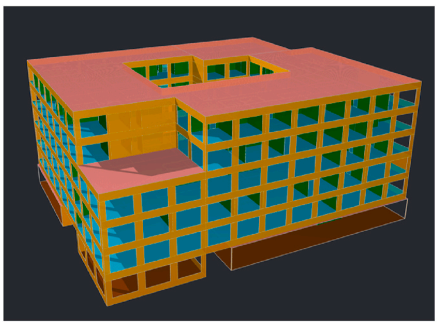

Fig. 8. Office building imported spaces in OSA.

and building operations to optimize the performance of the building.

Fig. 10 further analyses the environmental impacts linked to the total materials demand, evaluating the weight of the different material types found in the BIM. Concrete dominates most categories, with a total contribution ranging from 43 to 92%. This can be attributed to two factors: the large environmental footprint of concrete production, and the nature of the BIM process. In this BIM, structural elements defining the geometry of the building such as concrete were typically considered first, while other materials such as metal products (piping, cables, etc.) were left for a later stage of the design process. As to the material resources impact category, gypsum has the largest contribution accounting for 50% of the overall impact. Finally, steel can also be highlighted, with a contribution ranging from 14 to 36% for carcinogenic impacts.

Fig. 11 shows the impacts on climate change from the operation of the university building under the three different scenarios co-simulated. Decreasing occupancy and operation in the "Reduced" scenario resulted in a 56% reduction of the total environmental impact. This reduction increased to 61% in the "Reduced_0 ht" scenario, where the heating load was reduced compared to the former scenario. Given the linear nature of the LCA framework, a similar variance ratio can be found across all the different impact categories.

It should be explicitly clarified that the representation of GWP in Figs. 11 and 15 has been abstracted, where a single data point for each month has been plotted for ease of dissemination in paper format, via a user interface, these data points can be viewed in full (10-min time-steps). Figs. 11 and 15 similarly demonstrates the time-series plot over a monthly period.

When analysing the results from Figs. 9 and 10 in contrast with Figs. 11 and 12, one can see the value that can be derived from time-differentiated results. Figs. 9 and 10, show LCA results from the traditional static LCA perspective. In contrast, Figs. 11 and 12, provide a time dimension to the GWP of the building as a whole.

This allows the designer or manager to assess and intervene at a more granular and accessible level. For instance, whilst Fig. 9 quantifies *what* element (heating, electric or material) has the greatest impact (on a given category) Fig. 11 indicates *when* that element has a greater or lesser impact. When considering this with the ability to simulate different scenarios one can assess *when* interventions have the greatest resulting impact. For instance, changes in operation between the scenarios in Fig. 11 had a great impact on GWP in May but little to no effect in December. Designers and managers are thus able to understand their impact on a much greater level.

Finally, it is noteworthy that whilst this study demonstrates different scenarios in the building usage, the developed framework would also allow the construction of different scenarios with respect to the demand for materials via the user interface (see Fig. 4). However, within the context of this research and whilst the potential influence on the material demand for an already constructed building is minimal, it has been left out of the scope of this work. However, it would be relevant in the design phase of other projects.

5.2. *Case study 2 – office building, belval*

For this case study, Fig. 13 shows the LCA results for the materials footprint and energy consumption of the office building model. As in the previous case study, impacts related to the building's material demand dominate most categories, while energy consumption becomes more relevant regarding climate change and energy resources. However, in this case, electricity and heating consumption show a different share of

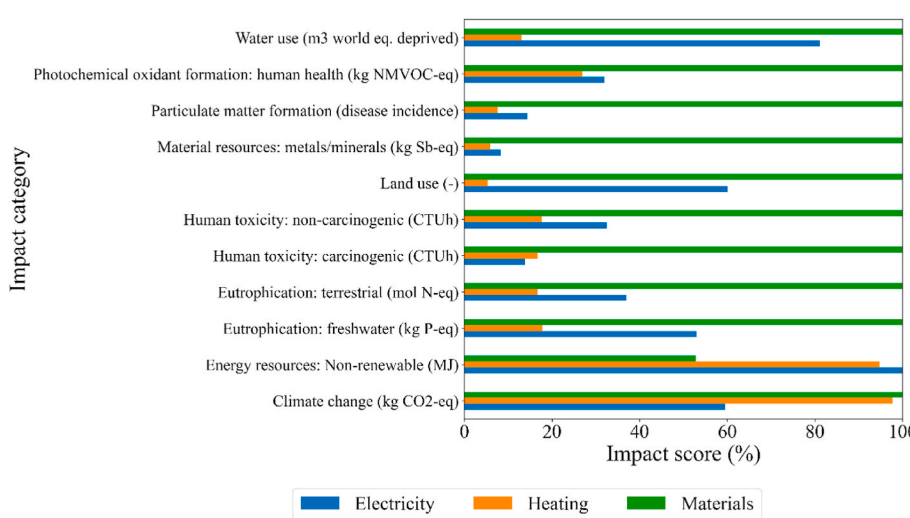

Fig. 9. Results for the life cycle impact assessment of electricity, heating, and materials of the university building during the period evaluated. Results are normalised to the highest results from each impact category.

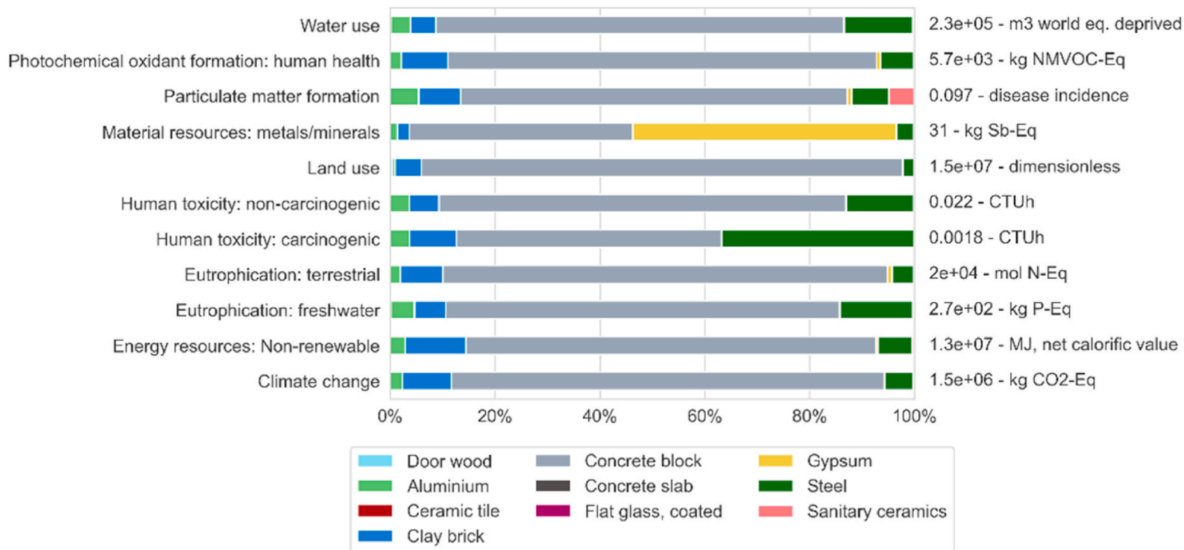

Fig. 10. Contribution analysis of the different material types to the total environmental impact of construction materials demand.

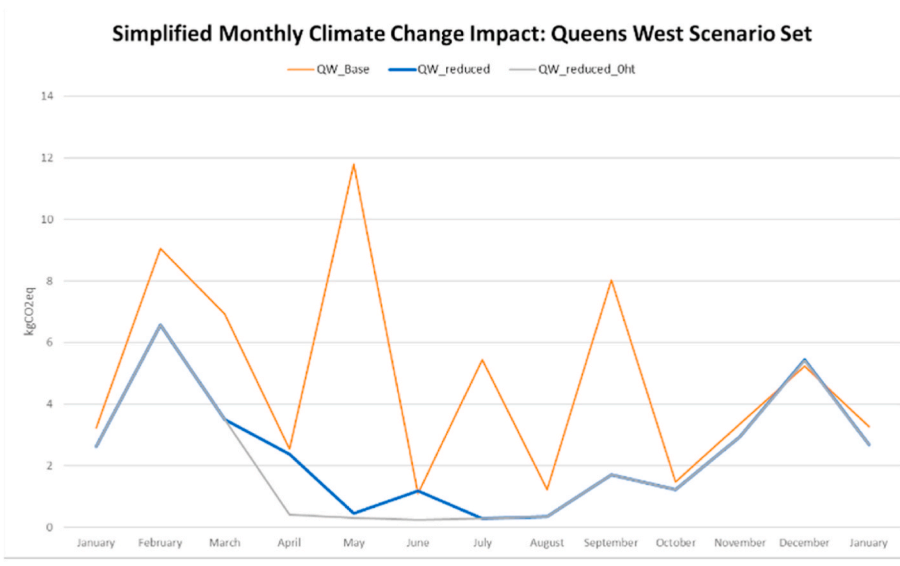

Fig. 11. Yearly time series of the university building LCA results for Global Warming Potential (kg CO2eq) for the three different scenarios assessed.

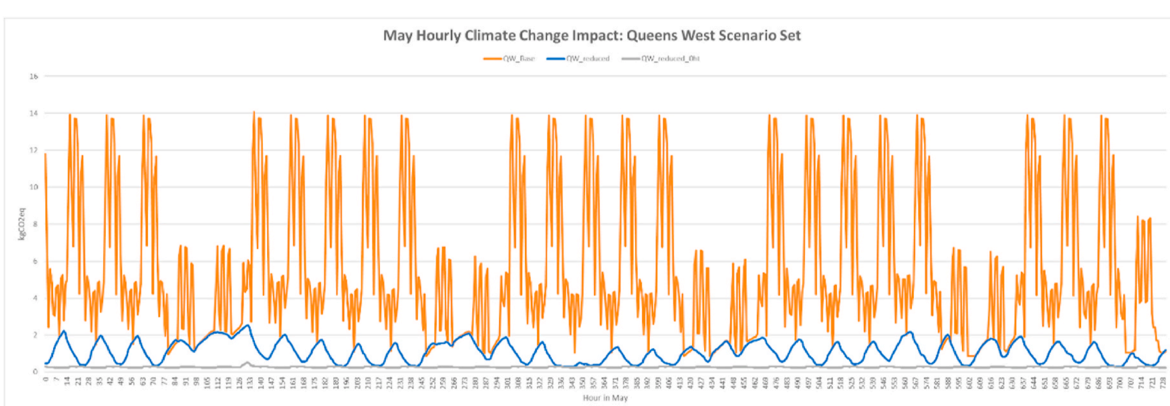

Fig. 12. May Hourly Climate Change Impact for the university building in Cardiff.

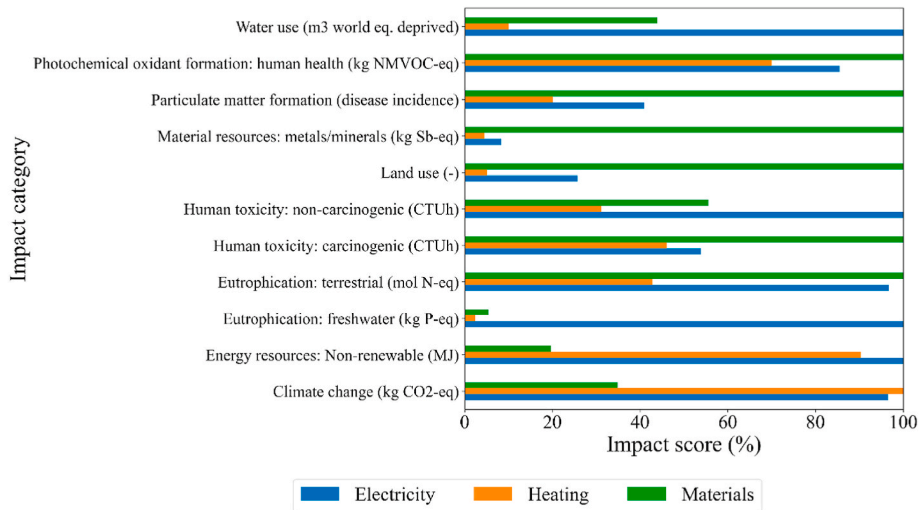

Fig. 13. Results for the life cycle impact assessment of electricity, heating, and materials of the office building during the period evaluated. Results are normalised to the highest results from each impact category.

the total impact across the different categories. As the energy consumption data fed by the BES is higher, it is observed an increased weight of heating and electricity consumption in most impact categories – including climate change and water use. Nevertheless, this weight variation is also explained by the inclusion in the BIM of additional materials such as plywood (see Fig. 14). In this line, it is possible to observe an increased contribution of materials demand for impact categories such as land use. It is noteworthy that in this case the BIM does not include steel, which was identified as one of the main contributing materials in the Cardiff case. This comparison with the previous case study highlights the dependence of this approach on the quality of the BIM.

Fig. 15 shows the impacts on climate change from the operation of the office building under the three different scenarios presented. Decreasing occupancy and operation in the “Reduced” scenario diminished the total environmental impact by 72%. This reduction increased to 74% in the “Reduced_0 ht” scenario, where the heating load is reduced compared to the previous scenario.

With the time-differentiated results in Figs. 15 and 16, one can discern that the interventions made across the three scenarios had a great impact on the environmental performance of the building in months such as February, March, April and May but much less effect in June and November. More specifically, this study found that between the interventions in scenarios 2 and 3, interventions at certain times in the day had little effect on performance.

This section has illustrated the value that can derived from time-differentiated LCA results. In simple terms, the benefits of such results over traditional static LCA results for a given period are primarily the dimensioning of environmental impacts over time, which in turn provides capability for the assessment of the whole building at a much more granular level than previously possible. At this granularity, designers and managers can explore and understand the outcomes of their interventions with much better accuracy (being able to capture exactly when the benefits occur as opposed to benefits gained over an aggregated period) and with much better focus on what and when the focus of improvements should be.

6. Discussion

This section analyses the results from Section 4 and 5 and describes the findings and limitations of this study.

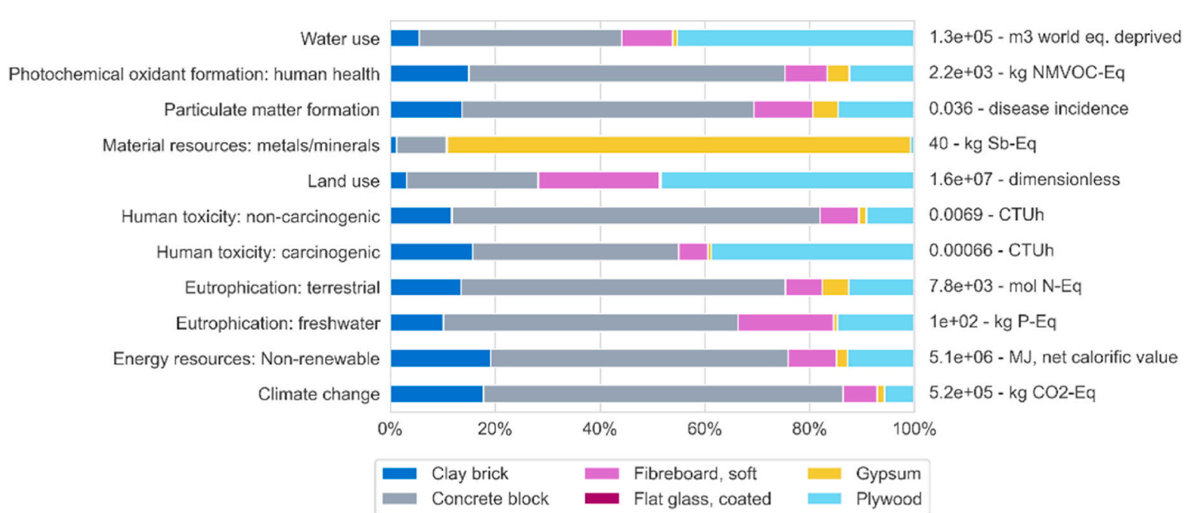

Fig. 14. Contribution analysis of the different material types to the total environmental impact of construction materials demand.

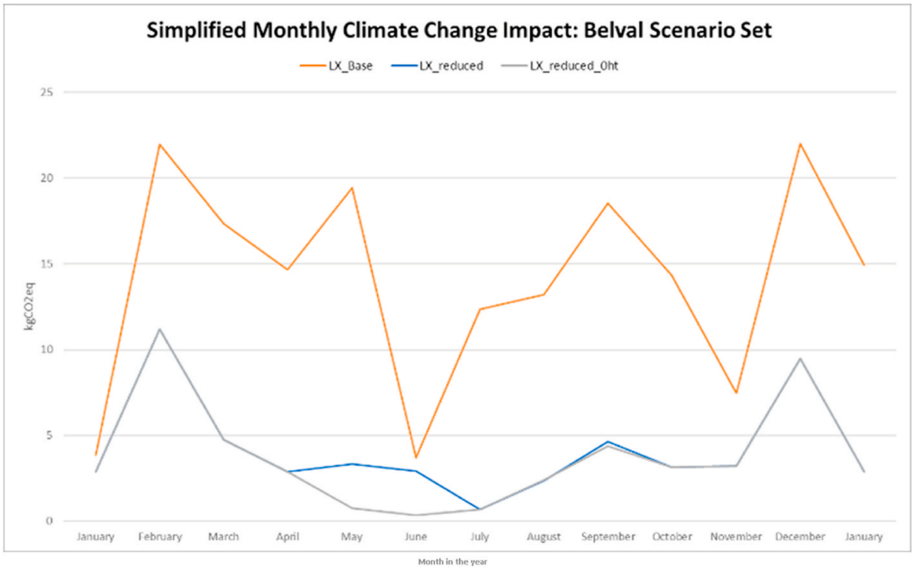

Fig. 15. Yearly time series of the office building LCA results for Global Warming Potential (kg CO2eq) for the three different scenarios assessed.

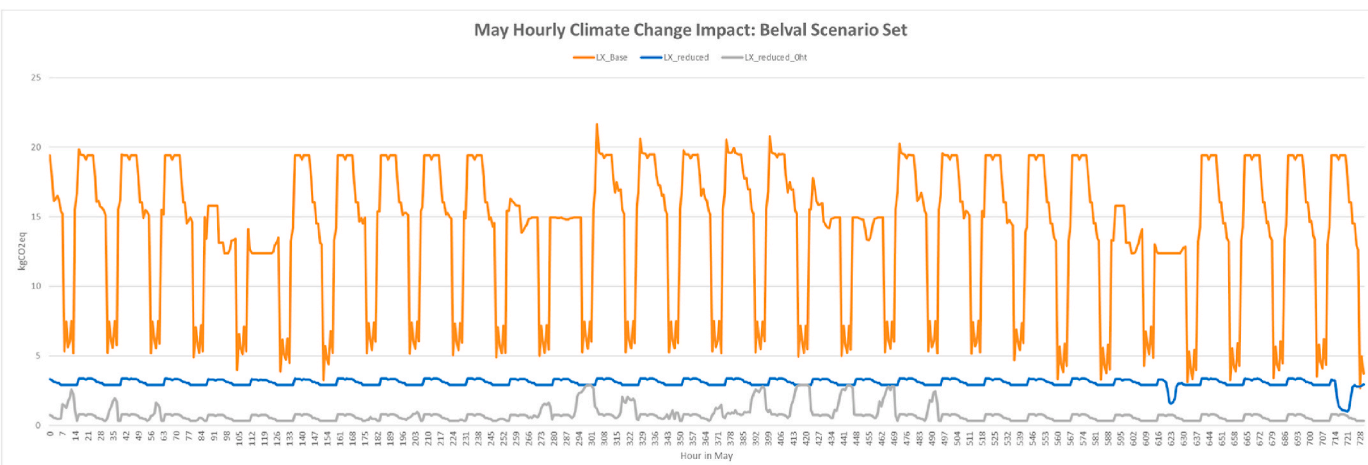

Fig. 16. May Hourly Climate Change Impact for the office building in Belval.

6.1. Findings

This study has developed and validated an open BIM based co-simulation architecture for BES and LCA, applicable to whole buildings across both construction and operational phases. The developed architecture is the first to tightly-integrate E+ and BW2, both fully-fledged simulation software tools for BES and LCA respectively. It is also the first to integrate LCA and a nationally (UK) approved software program for BES [5].

The integration of E+ and BW 2 has allowed this research to maintain a dynamic foreground inventory for electricity, heating and water. This approach provides more accurate estimates and time-differentiated results, enabling analysis at a more granular level, allowing for investigations at particular points in time.

The co-simulation architecture can provide a fully-fledged assessment of building energy and life cycle impact from the early design stage. Application at the point of BIM creation reduces labour, time, and cost, in particular, removing the need to recreate geometry in multiple software applications. Further, whilst many consultancies or practices depend on proprietary software application and the associated commercial support, this open BIM based architecture presents little capital barriers and so, enables BES and LCA co-simulation available to individuals or organisations beyond medium and large organisations. On this point, for organisations that have yet adopt BIM processes, this study further incentivises the use of BIM. In comparison to the status-quo of modelling practices, there are no particular barriers to the scalability of this approach.

The most time-consuming task in energy modelling is the creation geometry alongside assignment of inputs such as constructions, internal gains and schedules [4]. This study makes a step forward by circumventing geometric problems with spaces and successfully converting the material properties. Further, internal gains and operation profiles/schedules are applied via the UI, used as an interface to tightly integrate E + BW2.

Finally, this study demonstrates three different scenarios, representing variations in the building usage across the COVID-19 year. In terms of outcomes, this demonstration resulted in findings aligned with other studies [34], such as the ease of rapid test performance, ease of sub-system modelling distributed amongst a parallel team and a scalable approach. Regarding practical implications, this study has developed a clear and repeatable methodology for the co-simulation of BES and LCA - making a step forward in the co-simulation state of the art – which will enable and encourage further works in the co-simulation area. For industry professionals, this study presents a guide to provide time-differentiated/dynamic LCA results from BIM, addressing the demand to move beyond static LCA data, whilst simultaneously reducing time demands and cost. This architecture represents a streamlined process that may be used to investigate various scenarios to reach forecasted environmental targets. Whilst validated against buildings in the United Kingdom and Luxembourg, pursuing environmental agendas and targets is a global issue and so, this study seeks to provide an architecture that may be used by researchers, designers and managers and policy makers to reach/investigate their targets.

6.2. Limitations

This subsection discusses the limitations around the developed co-simulation architecture. This study has developed an "open" approach, however, it should be explicitly noted that in both case-studies, the open co-simulation architecture was applied to BIM models authored in proprietary tools, the potential for BIM models authored in open/free programs is discussed in section 6.3.

Similarly, to other studies [8,12], these works experienced geometric discrepancies, though this problem was circumvented by the enrichment of the BIM model with spaces as described in section 4.2.2. For these purposes, this was a satisfactory solution for the context of the building design process, as spaces are typically defined during early BIM authoring for functions such as floor plan legends. Therefore, lossless visual geometry was not the focus of this study.

In terms of the other enrichment challenges, site-location and material properties were applied within the user interface, however internal gains, systems and building operation schedules were not representable/transferable in BIM software and these were modelled in the initial OSM creation and edited via the user interface.

The integration of E+ and BW2 has allowed this study to maintain a dynamic foreground inventory for electricity, heating and water. However, the foreground activities are only linked to static background processes from the LCI database ecoinvent.

In comparing two case studies non-domestic buildings, this study has highlighted the dependence of this approach on the quality of the BIM. As in the case of any other simulation, the results can only be as good as the inputs and so, the results here demonstrate the clear need for guidance on the minimum standard quality level of BIM's.

Finally, when considering the challenges in the implementation of this architecture in practice, there are several challenges. Typically, most building energy models used for non-domestic purposes are authored and developed in proprietary simulation software such as IES, in-part due to the technical support provided by vendors. Whilst the benefits of the architecture disseminated in these works incentivises the use of BIM, it does not alleviate the desire or need for technical support from design consultancies. In order to engage with this architecture, consultancies would need to rely on in-house expertise that they may or may not possess.

6.3. Future research

This study constructed scenarios to reflect building usage over the COVID-19 2020 year, however different scenarios with respect to the demand for materials would be interesting to pursue, with particular relevance in the design phase of other projects. More specifically, this study has demonstrated the benefits in terms of time-dimensioning, accuracy and granularity in the investigation of operational scenarios, an investigation around scenarios focusing on the use of various materials in a building project would provide a time-dimension assessment not applied in current practices. Similarly, whilst this co-simulation architecture has been applied to whole-buildings, future work could consider the scalability of this approach on building stock.

Having tightly integrated two models describing building behaviour, opportunities exist to extend the model further, one such example being the extension of a separate occupant behaviour software module as in Ref. [40]. As mentioned in Section 5.2.1, validation of this co-simulation architecture against HBjson would be valuable, this would enable more possibilities for users familiar with the HoneyBee suite.

From the LCA perspective it would be interesting to complete the dynamic perspective of these works, here, the foreground activities are only linked to static background processes from the LCI database ecoinvent. This dynamicity can be very relevant specially for the electricity, as the electricity mix providing the necessary energy is changing over time.

Lastly, whilst this study has focussed on the technical validation of the presented co-simulation architecture, it would be a suitable exercise to evaluate the current policy-making and regulation landscape in regards to energy and environmental impact reporting. In particular, a pertinent exercise could investigate the use of this architecture in addressing national climate targets.

7. Conclusion

This final section concludes this study, these works have been conducted with the aim of addressing the lack of tightly coupled building co-simulation approaches – dynamic or otherwise - integrating BES and LCA.

Background information and a systematic review of the state of the art in co-simulation within the building domain has been presented in sections 2 and 3, respectively. This review identified that, only one study has attempted to integrate BES and LCA. This study has identified that whilst the development of approaches to allow the coupling of different domain models to effectively describe the interaction between different parts of the building is key for the advancement in building related research, studies fully integrating BES and LCA are lacking and in most cases are used as distinct methodological approaches.

Towards this aim, this study has investigated the following research question: How can the tight integration of an BES and LCA aid the design and management of buildings?

To address this research question and identify the benefits of such a co-simulation, this study has developed an open BIM based co-simulation architecture tightly integrating E+ and BW2. To validate this co-simulation architecture, two case study buildings – located in the United Kingdom and Luxembourg – have been co-simulated. For each building, three "scenarios" have been explored, encompassing both the construction and operational phases of a building's lifecycle. This study further provides analysis and discussion around the results derived from such a time-differentiated BES and LCA co-simulation and provide an indication of potential avenues of future research. This analysis has identified that the benefits of time-differentiated LCA results over traditional static results are; the dimensioning of environmental impacts over time, and the provision of the capability for the assessment of the whole building at a much more granular level than previously possible.

At this granularity, designers and managers can explore and understand the outcomes of their interventions with much better accuracy. They can capture exactly when the benefits occur as opposed to only understanding the benefits gained over an aggregated period and with greater ability to identify what and when the focus of improvements should be.

Regarding practical implications, this study has developed a clear and repeatable methodology for the co-simulation of BES and LCA - making a step forward in the co-simulation state of the art – which will enable and encourage further works in the co-simulation area. For industry professionals, this study presents a guide to provide time-differentiated/dynamic LCA results from BIM, addressing the demand to move beyond static LCA data, whilst simultaneously reducing time demands and cost. This architecture represents a streamlined process that may be used to investigate various scenarios to reach forecasted environmental targets. Whilst validated against buildings in the United Kingdom and Luxembourg, pursuing environmental agendas and targets is a global issue and so, this study seeks to provide an architecture that may be used by researchers, designers and managers and policy makers to reach/investigate their targets.

Finally, where traditional LCA results may identify *what* impact an element of interest has, this co-simulation architecture describes *when* that element has a greater or lesser impact. In this manner, a user can better assess *when* interventions have the greatest resulting impact, thus providing a more complete understanding of the building, which is a step forward in effectively and holistically describing the behaviour of buildings.

Author contribution

Jonathan Yeung: Conceptualization, Methodology, Validation, Investigation, Writing – original draft, Writing – review & editing, Visualisation, Alvaro J. Hahn Menacho: Methodology, Validation, Investigation, Writing – original draft, Antonino Marvuglia: Writing – original draft, Tomás Navarrete Gutiérrez: Software, Thomas Beach: Conceptualization, Writing – review & editing, Supervision, Project administration, Funding acquisition, Yacine Rezgui: Conceptualization, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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