

An Investigation into GHG and non-GHG Impacts of Double Skin Façades in Office Refurbishments

Francesco Pomponi, Poorang A.E. Piroozfar, and Eric R.P. Farr

Keywords:

building energy use
demand-side technology
double skin façade
environmental impact assessment
life cycle assessment (LCA)
low-carbon refurbishment

 Supporting information is available on the JIE Web site

Summary

The building sector is a major contributor to energy consumption, greenhouse gas (GHG) emissions, and depletion of natural resources. In developed countries, existing buildings represent the majority of the stock, their low-carbon refurbishment hence being one of the most sensible ways to mitigate GHG emissions and reduce environmental impacts of the construction sector. This article has investigated and established the GHG and non-GHG life cycle impacts of several double skin façade (DSF) configurations for office refurbishments by means of a parametric comparative life cycle assessment against up-to-standard single skin façade (SSF) refurbishment solutions. Two different methods were used to assess both GHG emissions and other environmental impacts. Results show that if, on the one hand, most of the DSF configurations assessed actually reduce GHG emissions compared to SSFs over their life cycle—thus supporting a wider adoption of DSFs for low-carbon refurbishments—on the other hand, there exist non-negligible ecological and environmental impacts that the DSF generates, specifically in terms of some materials of the structure and their final disposal. Research attention is thus needed regarding the environmental impacts of the materials used for DSFs and not only in minimizing the energy consumption of the operational phase.

Introduction

In refurbishments, improvements to the façade are arguably one of the most effective strategies to reduce energy consumption and mitigate carbon dioxide (CO₂) emissions of a building (IEA 2014). This is particularly relevant for the UK, where buildings account for over 40% of national energy consumption and CO₂ emissions (DCLG 2012b). Within the UK nondomestic sector, 75% of buildings were built before 1985 (Carbon Trust 2009) with 60% to 90% of them predicted still to be standing in 2050 (IEA 2014). Further, only 1% to 2% of the building stock is newly built each year (CIBSE and BSRIA 2007). Existing buildings offer therefore the greatest opportunity for decreasing CO₂ emissions and energy consumption (Thomas 2010).

Within the nondomestic sector, offices alone consume around 40% of energy (Pérez-Lombard et al. 2008). Nevertheless, existing office buildings remain largely untouched, and many refurbishments fail to deliver low-carbon buildings (CIBSE 2013b) despite that innovations in nondomestic buildings could save 86 million tonnes (Mt) of CO₂ by 2050 (LCICG 2012). Reducing energy demand through retrofitting the existing building stock is therefore a priority (Stevenson 2013), and one of the major challenges for the future is “to promote the sustainable refurbishment of that consolidated [building] stock” (Ferreira et al. 2013, p. 1454).

In this respect, glazed double skin façades (DSFs) are among the best façade technologies to reduce energy consumption and

Address correspondence to: Francesco Pomponi, University of Cambridge, Department of Engineering, Centre for Sustainable Development, Trumpington Street, Cambridge CB2 1PZ, United Kingdom. Email: fp327@cam.ac.uk Web: www.researchgate.net/profile/Francesco_Pomponi

© 2015 by Yale University
DOI: 10.1111/jiec.12368

editor managing review: Edgar Hertwich

Volume 20, Number 2

greenhouse gas (GHG) emissions from the demand side, while helping manage efficient interactions between out- and indoor conditions (Shameri et al. 2011). A DSF consists of a glazed skin installed in front of the actual façade from which it is separated by an air cavity that acts as a ventilation shaft. In moderate climates, DSFs seem capable of significant (30% to 60%) reductions in operational energy (e.g., Brunoro 2008; Cetiner and Ozkan 2005; Gratia and De Herde 2007), and their behavior in the operational phase has been widely studied and is fairly well documented. To the contrary, very little knowledge exists about DSFs' embodied¹ figures and the overall life cycle environmental impacts (LCEIs).

In life cycle assessments (LCAs) of buildings and construction products, the use of the global warming indicator (GWI) as a single-issue method represents common practice in the architecture engineering and construction (AEC) industry. Nonetheless, being reductionist by nature, this approach neglects other environmental impact categories (Dahlström et al. 2012), which may result in oversimplification (Asdrubali et al. 2015) and lead to erroneous judgments about environmental consequences (Turconi et al. 2013).

This article assesses the LCEIs of DSFs in refurbishments, through a cradle-to-grave LCA with a twofold aim. First, it utilizes GWI to establish whether DSFs can be considered as a low-carbon technology; thus, their use in refurbishment could/should be further encouraged. Second, it aims to investigate whether relevant differences arise when GWI results are analyzed against impact results from a more comprehensive assessment method (i.e., ReCiPe) to critically determine whether and where GWI may fail to represent non-GHG environmental impacts that would inform conclusions from, and outcomes of, the LCA.

Specifically, this article aims to answer the following research questions:

1. In a cradle-to-grave LCA, are DSF refurbishments preferable to single skin solutions from a GHG impacts perspective?
2. When GHG impacts are evaluated along with non-GHG impacts,
 - a. Is GWI a reliable enough and representative indicator? and,
 - b. Which new insights, if any, will arise when the focus switches from a merely global-warming-based assessment to a more comprehensive assessment method?

The article starts with a critical literature review of LCA in the AEC industry and continues on to DSFs as a technology with potential application to façade refurbishment, highlighting the need for a fresh outlook into this demand-side technology from a more holistic, environmental perspective. Next, the design and methodology used for this research are elaborated on. Elucidating on the functional unit (FU), system boundaries and deployed options, data collection, and operational energy modeling is the next step in setting up the design for this research. Results follow, which are then interrogated through a discussion of findings. A summary of the main findings, limita-

tions, and recommendations for further research concludes the article.

Literature Review

Life Cycle Assessment in the Architectural Engineering and Construction Industry

Sustainability assessment of buildings throughout their life cycle is currently not regulated by policy in Europe (Moncaster and Song 2012). LCA scenarios are inconsistent and varying with regard to settings, approaches, and findings, and there are major impediments in the way of consolidation and comparison of results. Different lifetime figures, lack of parametric approaches addressing multiple scenarios, little clarity in the FU considered, diverse methodologies and methods for conducting the studies, and the focus mainly on real buildings—which makes any generalization hard to put together—are the most important reasons (Cabeza et al. 2014). Such diversity is justified by, and originates from, the inherent complexity of the construction sector where each of the materials used has its own specific life cycle and all interact dynamically in both temporal and spatial variations (Collinge et al. 2013; Dixit et al. 2012; Erlandsson and Borg 2003). Additionally, the long life span of buildings combined with change of use during their service life imply lower predictability and higher uncertainty of variables, parameters, and future scenarios (Buyle et al. 2013; Dixit et al. 2012). Such difficulties eventually lead to taking a “reductionist” approach in many recent LCAs, where the term “simplified” often recurs openly representing such a nature (Bala et al. 2010; De Benedetti et al. 2010; Malmqvist et al. 2011; Wadel et al. 2013; Zabalza Bribián et al. 2009).

Some scholars have studied the relevance of simplifications in LCAs of buildings and their components, concluding that a simplified approach does not lead to different results from those of a detailed assessment, although it cannot be stated that more comprehensive assessments are not necessary in any circumstance (Kellenberger and Althaus 2009). In such a complex scenario, existing LCA International Organization for Standardization (ISO) standards fail to provide a sound methodology to execute the assessment (Dixit et al. 2012; Zamagni et al. 2008) and lack mathematical modeling for performing calculations (Heijungs et al. 2009). To address and facilitate some of these issues, the European Technical Committee CEN/TC 350 has developed standards that look at the sustainability of construction works with the aim of quantifying, calculating, and assessing the life cycle performances of buildings (BSI 2010). Those standards have recently been used to develop tools to evaluate the embodied carbon and energy of buildings (Moncaster and Symons 2013). These tools echo the focus on GWI as the assessment method when analyzing impacts of buildings and their components from a life cycle perspective (Ardente et al. 2011; Hammond and Jones 2008; Ip and Miller 2012; Monahan and Powell 2011; Pauliuk et al. 2013; Radhi and Sharples 2013).

The emphasis on carbon and energy and the use of GWI as a method to assess GHG emissions have been described as a crude approach, but also beneficial to ease understanding and enhance transparency (Weidema et al. 2008). This is both understandable and well received, considering that far too many studies still focus solely on operational energy, despite embodied energy often accounting for more than half of the life cycle energy (Crawford 2011), with peaks of up to 70% in the UK (Ibn-Mohammed et al. 2013). Nevertheless, GWI fails to account for important environmental impacts (Asdrubali et al. 2015), such as eco-toxicity and human toxicity, or water and land use, and may lead to erroneous judgments about environmental consequences (Turconi et al. 2013). These limitations have been highlighted in literature chiefly in industries other than construction, with biofuels as the most cited field (Guinée et al. 2011; Weidema et al. 2008).

In the specific case of buildings, they are large, complex, unique, and involve a broad range of materials and components, which, in turn, hold various environmental impacts that are not only difficult to track, but also challenging to assess and interpret (Dixit et al. 2012). Therefore, in accepting the LCA role of facilitator to help identify the least damaging alternative, the adoption of more comprehensive impact assessment methods combined with GWI is arguably a sensible way forward. With such a broader scope in mind, Scheuer and colleagues (2003) assess the life cycle environmental performance of a new higher education building by means of several impact categories, namely, GWI, ozone depletion potential (ODP), acidification potential (AP), and eutrophication potential (NP). Their findings suggest consistency throughout all the categories and identify the operational phase of the building as the one that accounts for the most significant impact. They therefore conclude that the “optimization of operations phase performance should still be the primary emphasis for design, until it is evident that there is a significant shift in distribution of life-cycle burdens” (Scheuer et al. 2003, p. 1061). Yet, owing to increased efficiency in insulating materials, and advancements in disciplines such as passive design, the balance between operational and embodied figures is significantly changing. In this respect, recent research suggests a major role of façade elements, which constitute “a substantial volume of the total consumption of materials used in a building and the need for maintenance of the façade makes it especially interesting from a life-cycle perspective” (Tellnes et al. 2014, 139).

Baldinelli and colleagues (2014) who assess the environmental performance of a wooden window by means of different impact categories (GWI, ODP, AP, eutrophication potential [EP], and photochemical oxidation) also suggest consistent results throughout the different categories used. In a comparative study about insulating materials, Nicolae and George-Vlad (2015) adopt primary energy demand, GWI, AP, eutrophication potential (EP), and photochemical ozone creation potential (POCP) as impact categories. Their results again show a fair consistency across all impact categories used, except POCP which is particularly influenced by the specific chemical composition of the insulation material considered.

Given the major role the construction sector plays toward the depletion of finite natural resources (Dixit et al. 2010), in addition to those impact categories identified in the literatures reviewed here, it seems particularly sensible to include impact categories aimed at assessing, where possible, resources depletion.

Life Cycle Assessment of Double Skin Façades

Only two studies (de Gracia et al. 2013; Wadel et al. 2013) exist where DSFs have been examined in detail from a life cycle perspective, despite that DSF is a technology widely used in the AEC industry with a strong belief that it delivers “green” buildings and is thus able to reduce environmental impacts. Further, both studies refer to specific façade typologies, located in well-defined and particular contexts, which are innovative products that do not represent the current practice in the AEC industry.

Concerns highlighted at the AEC level about LCAs seem to find evidence about the specific case of the DSFs as well. In fact, Wadel and colleagues (2013) adopt a *simplified* LCA for an innovative DSF with vertical shading devices placed at specific intervals and made out of recycled materials, as much as possible. The use phase is not incorporated in the LCA and impacts assessed throughout the study are embodied energy and CO₂ emissions, the FU being 1 square meter (m²) of the façade with a life span of 50 years. Embodied energy and carbon values for the best configuration of the DSF are 2,273.08 megajoules (MJ)/m² and 178.64 kilograms CO₂ equivalents (kg CO₂-eq)/m², respectively. From a comparative point of view, their results show that the DSF, in its best configuration, is capable of 50% less energy consumption and CO₂ emissions than conventional façades (Wadel et al. 2013).

de Gracia and colleagues (2013) conduct a cradle-to-grave LCA of a DSF with phase change materials (PCM) in its cavity. They utilize the Eco-Indicator 99 (EI99), an impact assessment method based on endpoints. This means that results from different impact categories are normalized and brought together to contribute to a final, single, cumulative score (known as the endpoint) for the product/process under examination (PRé Consultants 2000). The FUs used are two cubicles constructed in Spain, one with the DSF, the other without, with a life span of 50 years. Their results also prove a beneficial effect of adopting a DSF, for it reduces the environmental impact by 7.5% compared to the reference case (de Gracia et al. 2013).

Notwithstanding the importance of regional and local foci in LCAs, more generic perspectives could allow for a broader use of the methods and could also ease comparison of results within different contexts. A less context-specific environmental impact assessment of office façades has been done by Kolokotroni and colleagues (2004). A specific DSF configuration is just one among many more options they assessed for both naturally ventilated and air-conditioned offices, and therefore the researchers had to sacrifice the depth for the breadth of their investigation. Embodied energy and EI99 have been used as methods and the DSF has the highest embodied energy (2,120 MJ/m²), but

Bill of Materials				
Quantity	Description	Total	Unit	
3	clamps (actual product Art. No.*)	8.1	kg	
3.5	m profile (actual product Art. No.*)	19.25	kg	
1.5	m ² of aluminum for walkways (wide option)	12.447	kg	
0.6	m ² of aluminum for walkways (narrow option)	4.979	kg	
0.0011	m ³ of steel for bracket (wide option)	8.855	kg	
0.00484	m ³ of steel for walkways casing (wide option)	38.962	kg	
0.0005	m ³ of steel for bracket (narrow option)	4.025	kg	
0.00354	m ³ of steel for walkways casing (narrow option)	29.302	kg	
0.24	m ² of surface for zinc coating for bracket (wide option)	0.24	m ²	
0.968	m ² of surface for zinc coating for casing (wide option)	0.968	m ²	
0.12	m ² of surface for zinc coating for bracket (narrow option)	0.12	m ²	
0.728	m ² of surface for zinc coating for casing (narrow option)	0.728	m ²	
5.25	m ² of 12 mm glass (monolithic option)	157.5	kg	
10.5	m ² of 8 mm glass (laminated option)	210	kg	
0.76	mm of plastic layer (laminated option)	3.96	kg	
5	m of structural sealant	0.515	kg	
5	m of PVC sealing gasket	0.3475	kg	

* = sensitive information related to manufacturer/data provider

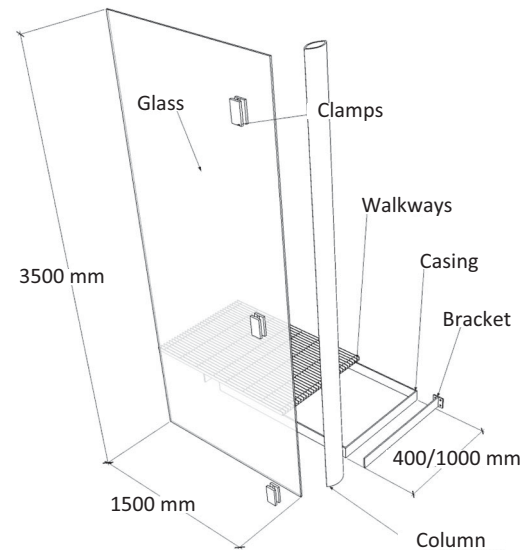


Figure 1 Exploded view and quantity details of the double skin façade (DSF) system.

the lowest EI99 score, for both naturally ventilated and air-conditioned offices.

Apart from these three studies, DSFs have not been investigated from a life cycle perspective, nor have they been studied in a refurbishment context in comparison with single skin solutions. In other words, the LCEs of DSFs are yet to be established comprehensively. As a consequence, primary data related to DSFs are still largely missing in the literature, mainly owing to a lack of data for glass processes, and echoes a known issue in the LCA community: the scarcity of reliable and complete data about buildings materials and assemblies, which, if they existed, would allow for greater environmental benefits (Crawford 2009; Peereboom et al. 1998; Reap et al. 2008).

Research Methodology and Design

Methodological Background and Impact Assessment Methods

Two main methodological approaches are commonly accepted by the LCA community: attributional LCA (ALCA) and consequential LCA (CLCA)² (Finnveden et al. 2009). owing to the specific focus of this research on DSFs as a product, ALCA is the approach chosen given that it focuses on physical flows to and from a life cycle and its components. It is also recommended by current British standards to assess GHG emissions of goods and services (BSI 2011) in order to define the inputs and their associated emissions/impacts related to the delivery of the product FU.

SimaPro is the tool adopted for this study. As anticipated, two different impact assessment methods have been used: the GWI over a 100-year horizon (IPCC 2013) and ReCiPe hierarchical³ perspective midpoint v1.10 (Goedkoop et al. 2013), which is a multicategory method commonly used in

LCAs. Midpoint modeling allows for higher transparency and lower uncertainty, whereas endpoint modeling shows things with more relevance, but can be less transparent and harder to compare (Bare et al. 2000; Blengini and Di Carlo 2010; Eldh and Johansson 2006). Owing to the unavailability of life cycle data for DSF, midpoint modeling with an aim at maximizing transparency was chosen.

System Boundary and Assessed Options

DSFs are defined by several parameters (Pomponi et al. 2013), including the geometry of the cavity and its width. The configuration chosen here is multistory, consisting of a cavity with no horizontal or vertical partitions. Alternative configurations, (e.g., corridor DSFs) are generally considered along with the heating, ventilation, and air-conditioning system and hence less likely to be applicable to refurbishments. The DSF analyzed in this study deploys an aluminium structure; what is broadly used across Europe and in the UK, for instance by ARUP, for the refurbishment of their headquarters in London (Gissen 2005).

Regarding cavity width, narrow and wide categories are widely acknowledged and we consider them both. Geometry of the building, data collected from visits to five construction glass manufacturing facilities, interviews with a leading façade engineering and manufacturing company, and the construction specifications and details all helped determine the FU—which is 5.25 m² of façade (figure 1)—and the choice of additional parameters, leading to the options in table 1.

The bigger the façade module the lesser costs and materials, with several advantages for the project; however, façade engineers suggested limiting the width to 1.5 meters (m) owing to excessive horizontal loads for wider façade modules with such a structural system, whereas 3.5 m corresponds to the height

Table 1 Realized and assessed options

Parameter	Options considered	Code	Number of scenarios	Details
Cavity	Narrow	CN	2	400 mm
	Wide	CW		1,000 mm
Glass composition	Monolithic	M	2	12 mm thermally toughened
	Laminated	L		8 mm + 8 mm + 1.52 mm PVB
Glass coating	Clear	CL	2	Clear float glass
	Coated	CO		Solar control glass
Aluminum manufacture	European (Central Europe)	Eu	2	Truck Euro: 4 to 500 km
	International (China)	Int		Transoceanic ship: 20,070 km Train: 140 km Train Euro: 4 to 120 km
DSF orientation	North	N	4	The building model is rotated to have the DSF facing each of the four main orientations.
	South	S		
	East	E		
	West	W		
Total			64	Possible permutations = $2^4 \times 4$
Single skin	North	SSN	4	The four single skin building models are used to establish the savings owing to the DSF in terms of operational energy.
	South	SSS		
	East	SSE		
	West	SSW		
Total scenarios			68	

Note: DSF = double skin façade; mm = millimeters; PVB = polyvinylbutyral; km = kilometers.

of the building story. The choice to evaluate an international supply for aluminum (with the sole focus on augmented transportation impacts) resulted from the interviews with the façade manufacturing company, which revealed that a substantial part of their aluminum supply comes from China. To the contrary, all five glass companies sourced glass from European Union (EU) countries.

Current regulations mandate that operations needed for a single skin refurbishment (e.g., improvement of wall insulation) are necessary in a DSF refurbishment as well. Therefore, common elements shared between the two refurbishments are excluded, and we drew the system boundaries around additional elements, (sub)assemblies, processes, and stages that a DSF would bear.⁴ In doing so, this study accounts for the surplus of materials and processes involved when DSF refurbishment is compared to single façade. These are represented in figure 2, which shows the flowchart for the FU and its system boundaries.

Data Collection

In terms of the data collection approach, three methods are found in built environment studies: process analysis, input-output analysis, and hybrid analysis (Crawford 2011). A

process-based analysis refers to a mix of processes, products, and location-specific data to calculate and establish the environmental impact of a product system, and in LCAs of buildings and their components it appears to be the most reasonable and detailed choice (Hammond and Jones 2008); it is also suggested by the TC350 standards. Primary data generated for this research, for which the permission to be disclosed was obtained, have been made available in tables S2 to S9 in the supporting information available on the Journal's website.⁵ Owing to data quality and reliability issues highlighted in the LCA literature review, process mapping and data collection were approached in a systematic way, starting from the flowchart in figure 2.

Each macro assembly in figure 2 has been broken down into subassemblies and, eventually, into elementary life cycle processes (ELCPs)⁶ that “follow the flows” that happen in reality. This reduces risks of double counting given that it follows the actual consequence of actions, processes, and events, switching from vertical (upstream/downstream) to horizontal (before/after) approaches. Single activities within ELCPs have been screened against the ecoinvent database and leading UK-based database (Hammond and Jones 2011), highlighting significant missing data mainly pertaining to glass-related activities, such as cutting, edging, drilling, heat soak testing (HST),

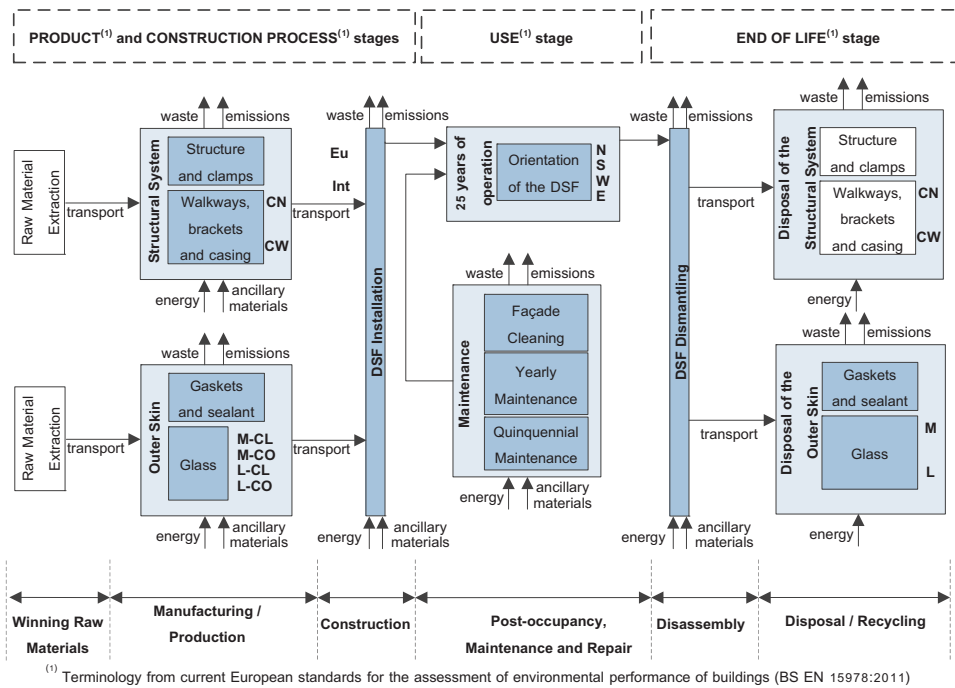


Figure 2 Flowchart for the functional unit (FU) and its system boundaries.

washing, and so on. To fill the substantial gap in available data in this area, five glass manufacturing companies and a leading façade firm have been contacted for primary data collection by means of interviews, site visits, and in-depth field study,⁷ to monitor processes and collect the data. Those assemblies in the white boxes in figure 2 are those for which ecoInvent data have been used. ecoInvent data have also been used for transportation impacts, as well as end-of-life (EOL) waste/recycling figures using the available scenario for England based on information from the Department for Environment, Food and Rural Affairs in the UK. All other assemblies are the result of a documented inventory and collected primary data. Close attention has been paid to the EOL of glass, given that monolithic and laminated types require different treatments to be either recycled or disposed of.

Data collected for glass processes proved particularly significant; specifically, glass edging is the process with the highest GHG impact. If we normalize the other processes compared to it, glass cutting and HST have values of 63.6% and 86.6%, respectively, again indicating their significance. Tempering, which was the only process available in the ecoinvent database, contributes to 28.4% of the total impact of the glass-related process. Without the data collection carried out, 71.6% of the glass-manufacturing-related impacts would have been neglected. Further, in the case of laminated glass, which, in our assumption, does not include the tempering of the glass panes, the totality of the glass-manufacturing-related impacts would have been neglected.

Input energy values for manufacturing activities used in this article refer to midvoltage energy delivered by the electricity network grid in Britain available from ecoInvent, which takes

into account UK energy mix figures. In terms of energy/carbon conversions, guidelines by Hill and colleagues (2011) have been used and two official documents published by the Department of Energy and Climate Change (DECC 2013a, 2013b), which provide GHG conversion factors ($1 \text{ kWh}_{\text{GAS}} = 0.20155 \text{ kg CO}_2\text{-eq}$; $1 \text{ kWh}_{\text{ELEC}} = 0.59368 \text{ kg CO}_2\text{-eq}$).

Case Description and Operational Energy Modeling

LCA literature provides case studies that are often based on specific buildings, thus hindering generalization of the conclusions and comparability of the results. Therefore, we have selected a generic, yet representative, office (figure 3) with a very slender built form and a cellular layout of internal spaces, which is the most common office building type in England (Shahrestani et al. 2013; Steadman et al. 2000). The building is located in London. It consists of nine floors of $66.6 \times 16 \text{ m}$, totaling $9,590 \text{ m}^2$ of treated floor area (TFA). Window to wall ratio equals 0.25, which is a typical and highly correlated value to offices of this type (Gakovic 2000).

Yearly operational energy consumption for space heating in both single and double skin models has been simulated through IES VE, a building energy simulation software used by academics and practitioners alike, and successfully deployed in DSF studies (e.g., Kim et al. 2013; Poirazis and Kragh 2009). IES includes a natural ventilation analysis module that addresses phenomena such as single-sided and cross-ventilation, and flow in cavities resulting from wind and buoyancy effects. Additionally, elements such as infiltration and thermal mass are also suitably dealt with (IES 2009). The aluminium structure obstructs, to some extent, the flow in the cavity, and the software vendor

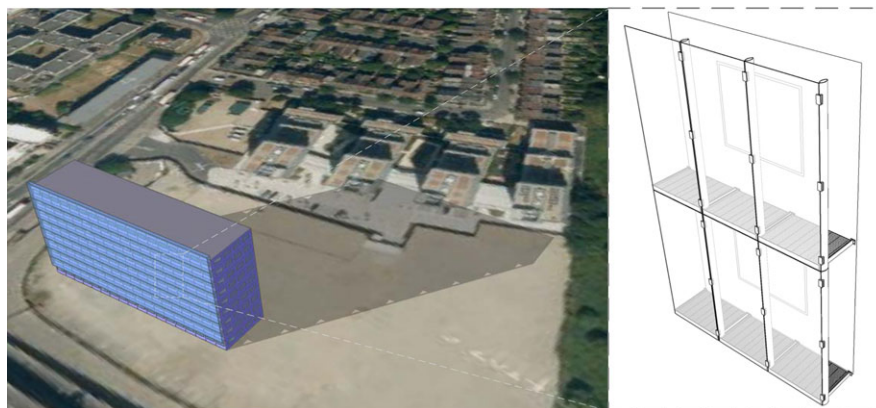


Figure 3 Aerial view of the building model superimposed on its location in London (Map data: Google, DigitalGlobe) with visual detail of the double skin façade (DSF).

recommends correction in such cases (IES 2012). Details are given in section S4 in the supporting information on the Web. The building is naturally ventilated, as are the majority of existing offices in the UK (CIBSE 2013b), thus narrowing our focus solely onto space heating loads.⁸ Space heating is provided by natural gas burning. Full details for the validity check of the simulations are given in section S3 in the supporting information on the Web.

Space heating energy demand is then translated into yearly loads in kWh/m²_{TFA} year. Such a heating load, however, refers to heating consumption of the building as a whole, and it is therefore necessary to allocate a share of it to the set FU. The step-by-step procedure developed and adopted for this study is shown in table 2.

With such an approach, results are compared like for like, strengthening the robustness of the results. The façade service life is assumed at 25 years, in line with studies specifically focused on building façades in the UK (Jin and Overend 2014). Additionally, offices undergo more frequent renovations owing to the change of ownership or use and the end of the leasehold (Tandy and Way 2004), which is not necessarily related to the EOL of building elements. Should the actual service life be longer, the energy savings of DSF would be higher, thereby making 25 years a conservative assumption.

Results

Operational energy results show that wide cavities slightly outperform narrow cavities with reference to the reduction of heating loads, except for the south orientation. These greater savings can be explained in comparison with the air gap in double-glazing units (DGUs), where it is shown that the wider the space between the two glass panes, the better the thermal performance of the DGU. Numerical findings in kWh/m²_{TFA} are shown in figure 4, which only presents 32 DSF options because the parameter for aluminum sourcing does not influence operational energy. Heating loads for the DSF options assessed range from 65.2 to 80.2 kWh/m²_{TFA} year and are in line with

both office energy benchmarks for the UK (CIBSE 2012) and previous figures about DSFs (e.g., Kolokotroni et al. 2004). Additionally, all models are close to “good practice” energy benchmarks for UK offices, showing the effectiveness of the refurbishment energywise (EEBPP 2000).

In a life cycle perspective, results presented here are in the form of GHG emissions (figure 5) and also for the following impact categories from ReCiPe: ODP (figure 6a); fossil depletion (figure 6b); freshwater eco-toxicity (figure 6c); human toxicity (figure 6d); and particulate matter formation (figure 6e). ReCiPe results for all the impact categories are given in table S10 in the supporting information on the Web.

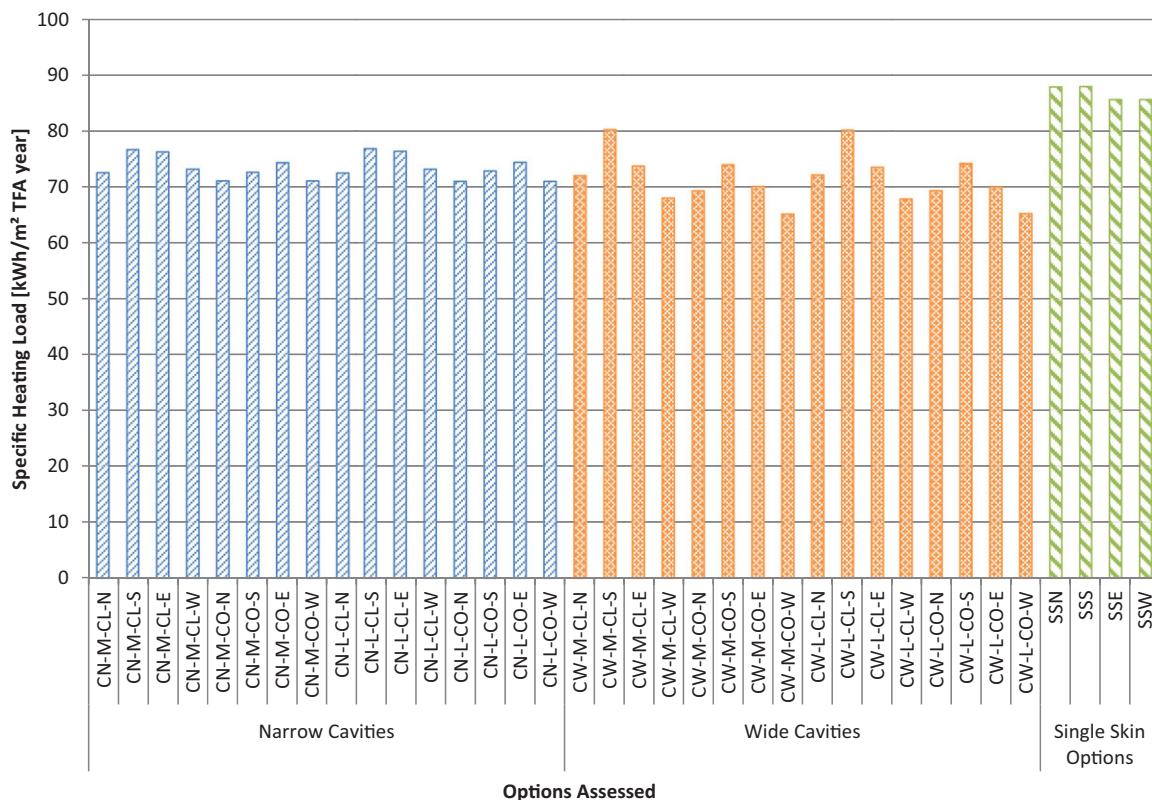
Numbers on the y-axis of figure 5a represent both the savings and augmented impacts in terms of kg CO₂-eq owing to the choice of DSFs over single skin façades (SSFs) as a refurbishment strategy. For example, the best configuration with a narrow cavity (CN-M-CO-N-Eu) is able to save up to more than 2,500 of kg CO₂-eq over the service life against its corresponding single skin counterpart, in view of augmented impacts of just over 1,000 of kg CO₂-eq. The operational GHG savings between DSFs and SSFs and the embodied GHG impacts of the DSFs are easier to read off figure 5b, where they are plotted over the two axes respectively. Further, full operational energy and GHG results are given in tables S8 and S9 in the supporting information on the Web, respectively.

GHG results highlight that the best performing wide cavity offers significantly higher savings than the narrow one, and operational energy is what accounts for the most (figure 5a). Figure 5b compares the operational savings of each option against its embodied impacts. Exact numbers are provided in the Supporting Information on the Web, but the figure allows for some interesting observations. Operational savings of narrow cavities are less spread than those of the wide ones. Additionally, owing to the different parameters considered in this research, there is a whole area in the middle where the two solutions equate both in terms of operational savings and embodied impacts.

Table 2 Step-by-step procedure to deal with operational energy figures of double and single skin models

Step	Task
#1	Yearly energy simulations are run for all the models
#2	Each DSF option is coupled with the equivalent single skin (SS) option (e.g. East oriented DSF models with East oriented SS models)
#3	The difference between the two is calculated, keeping the sign, be it positive or negative
#4	Considering that the two models are identical, apart from the DSF, whatever the difference it is reasonable to assume it is the sole responsibility of the DSF
#5	To allocate the FU its share, it is assumed that each m^2 of the DSF equally contributes to the final result. More specifically, the total difference is characterized in the form of $[kWh/m^2]$ by taking into account the total DSF area, and then multiplied by $5.25 m^2$ (the area of each FU) to attribute to the functional unit its share
#6	If the difference between DSF and SS is negative, DSFs are actually reducing the energy consumption of the buildings. As ours starts as a comparative study, we consider that energy reduction has a reduced environmental impact and, therefore, a negative contribution to the overall GWP. If it is positive, instead, DSFs are increasing the energy consumption and that energy contributes to increasing the overall environmental impacts of DSF. The yearly saved/augmented impacts are then extended to the lifetime of the façade, assuming energy performance does not decay over time.

Note: DSF = double skin façade; FU = functional unit; m^2 = square meter; kWh/m^2 = kilowatt-hours per square meter; GWP = global warming potential.

**Figure 4** Results from the operational energy simulations (heating loads).

In the results from ReCiPe, operational savings over SSFs are no longer significant. In fact, as high as operational savings can be, they have null or negligible benefits across all of the impact categories assessed through ReCiPe. To the contrary, assemblies and stages of the DSF and their embodied impacts suddenly become worthy of closer attention.

In this respect, figure 6a shows, with reference to ODP, how significant the glass-related processes are. For narrow cavities—which have a lower amount of metal—glass outweighs structure-

related impacts, whereas for the wide counterparts this does not hold true. Noticeable impacts are also related to maintenance activities and glass disposal. With respect to fossil depletion (figure 6b), maintenance activities and façade cleaning have even more significant impacts, although elements of the supporting structure bear the absolute majority of the loads. Freshwater eco-toxicity (figure 6c) brings the attention again to the importance of the elements of the supporting structure, whose impacts (both to produce and dispose of them) represent nearly

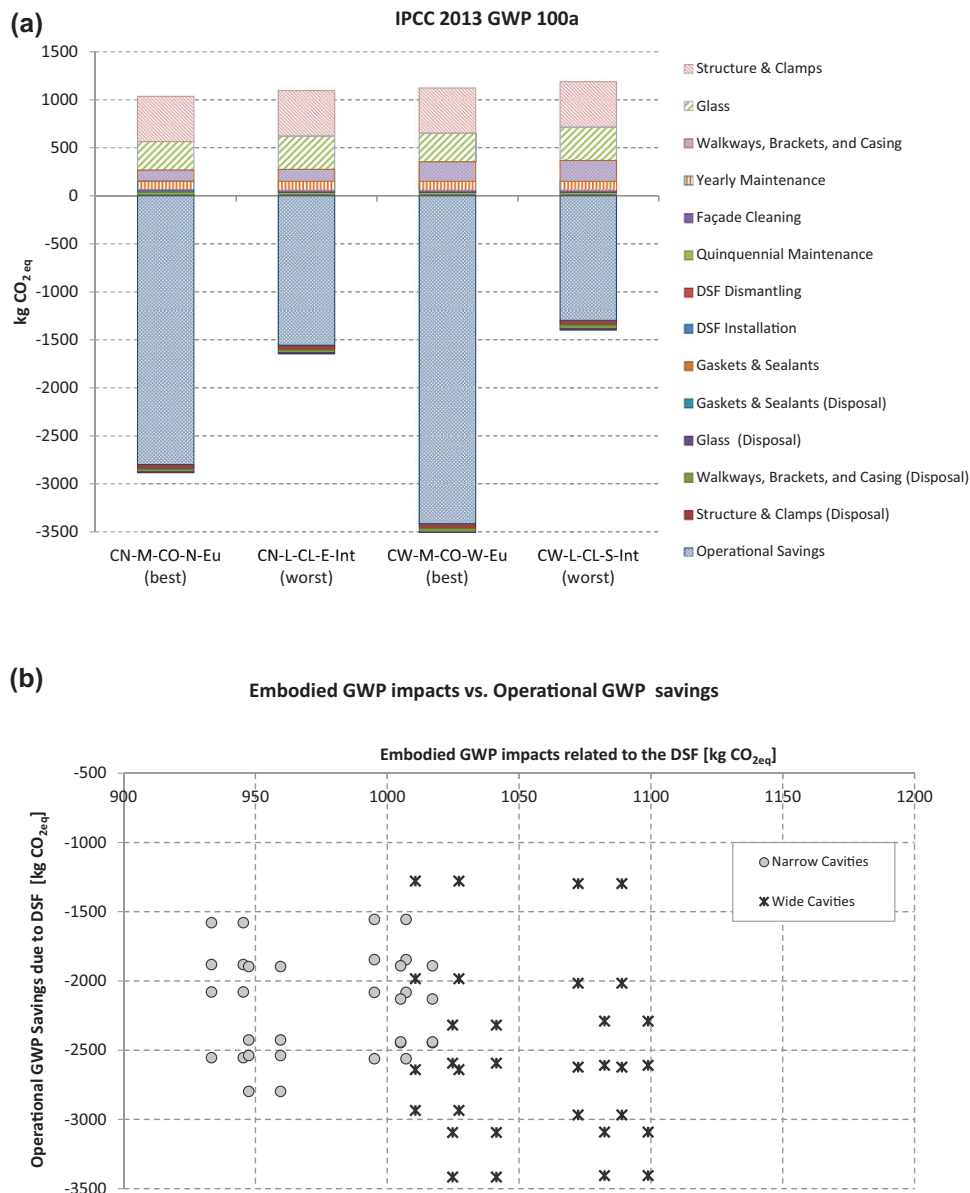


Figure 5 (a) Best and worst performing options for both narrow and wide cavities in terms of global warming potential (GWP) over 100 years under the assumption of a useful life of the façade of 25 years and (b) embodied impacts vs. operational savings for all 64 assessed scenarios. Codes as given in Table 1.

the totality of this impact category. Similarly, human toxicity (figure 6d) indicates glass and supporting structure as the assemblies responsible for the most impacts. Although units are the same for both impact categories in figure 6c and 6d, it is worth noting the difference in scales. Human toxicity figures are up to 20 times higher than those referred to freshwater ecotoxicity. Particulate matter formation (figure 6e) consistently indicates glass, components of the structure, and maintenance activities as elements of concern. Additionally, it shows well the benefits resulting from the recycling potential as recommended by TC350 standards, which can be seen as a negative impact. Such an element is also present in all other graphs,

although trade-offs are less evident. Finally, it needs be highlighted that monolithic glass options always show lower impacts than their laminated glass counterparts. This is an important result, which has been possible owing to the data collected. In fact, on the one hand, laminated glass does not necessitate tempering and HST, but the impacts of the polyvinyl butyral (PVB) plastic film, the lamination process, the higher thickness required to warrant comparable physical strength, and the influence that the plastic film has on the wearing of tools and consumption of ancillary materials needed to cut and edge this kind of glass, all outweigh tempering and HST savings.

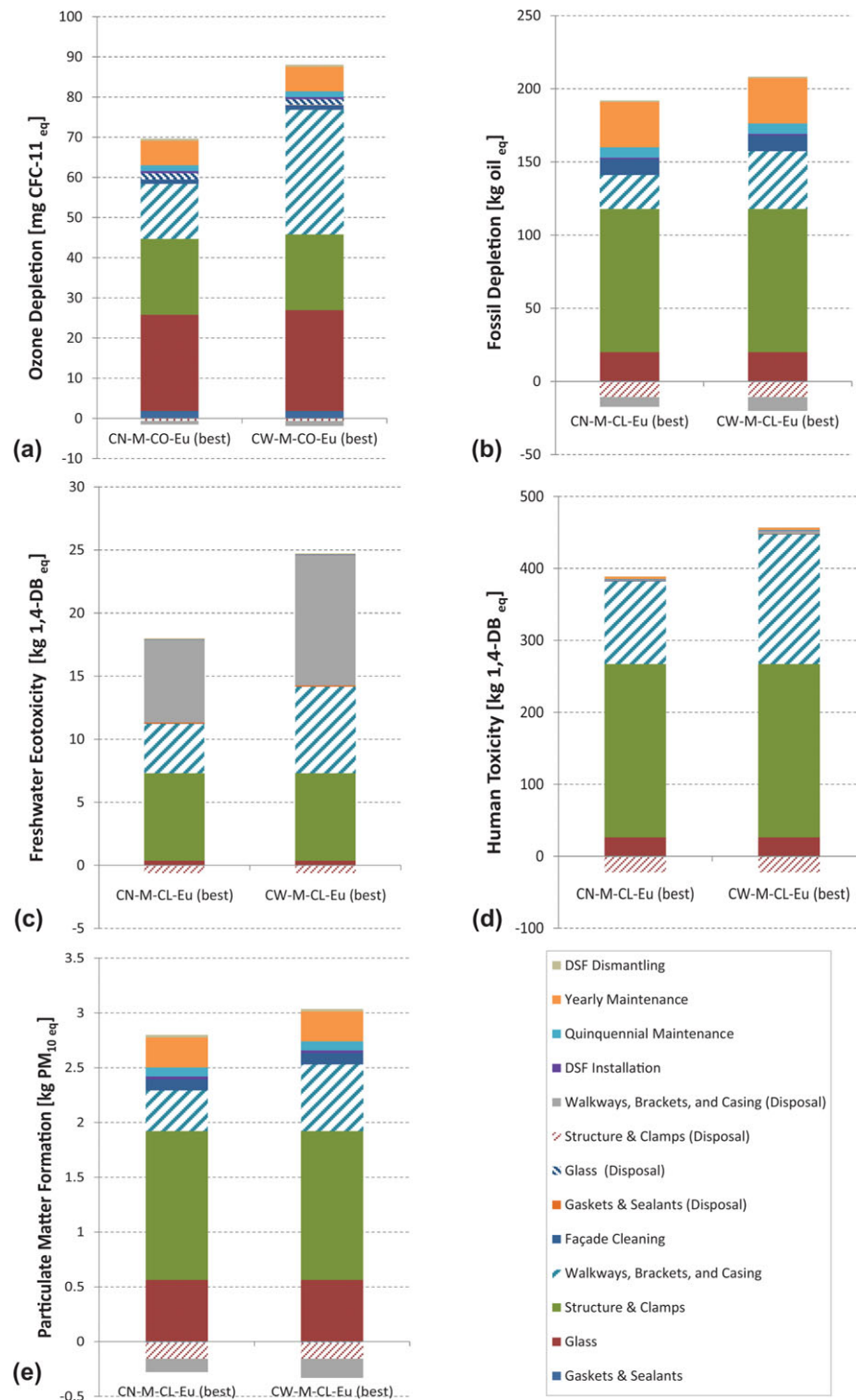


Figure 6 Best performing options for both narrow and wide cavities related to the impact categories of (a) ozone depletion, (b) fossil depletion, (c) freshwater ecotoxicity, (d) human toxicity, and (e) particulate matter formation.

Discussion of Findings

Following common practice in current LCAs in the construction industry, and looking at the GHG results, it can be concluded that the DSF options assessed within this research perform significantly better than single skins. Additionally,

GHG results can also be used to assess the ratio between embodied impacts and operational savings (see figure 5b and table S9 in the supporting information on the Web). For the options considered here, this ratio varies from 30% to 84%. The closer to 100% this ratio, the higher the risk that cumulative embodied impacts overcome savings during the operational phase. In

this article, none of the options assessed can be considered as at risk. In other words, the operational GHG savings that the DSF is capable to offer outweigh the GHG impacts related to the DSF production, installation, transportation, maintenance and repair, dismantling, and disposal. This is a significant finding, considering that no such comparative study has been carried out before. To fully understand the potential practical implications of this finding, a numerical assessment will be used. Offices in the UK total over 350 million m² as of 2008 (DCLG 2012a). An available benchmark about fossil-thermal energy (gas) consumption for a UK generic office is 120 kWh/m²_{TFA} year (CIBSE 2008). These two figures suggest that UK offices in 2008 were responsible for 42 million megawatt-hours (MWh) consumed every year, which—taking into account current conversion factors—correspond to nearly 8.5 Mt CO₂-eq/year. A study on the suitability of DSFs to renovate UK offices indicated that 67% of the existing stock could theoretically adopt a DSF when refurbished (Pomponi et al. 2013). The existing stock of UK offices used in this study corresponds to the year 2000, when offices in the UK totaled just over 300 million m² (DCLG 2012a). If those figures are combined with the average heating load of DSFs assessed in this research (72.5 kWh/m²_{TFA} year), it seems that a broad adoption of DSFs in the UK should be able to save yearly over 17 million MWh and 3.5 Mt CO₂-eq. However, these calculations are merely based on available statistical data and do not take into account many other determinants. Therefore, care should be taken before making bold claims or generalization in any shape or form. Nonetheless, it is worth noting that the yearly savings potential over a 25-year useful life of DSFs adds up to roughly one tenth of the reduction needed to meet the UK Climate Change Act target. Undoubtedly, DSFs, as a form of low-carbon refurbishment technology, deserve more attention than they are currently receiving.

Regarding the ReCiPe results, the options with the highest and lowest impact categories, identified with reference to the GWI (table S8 in the supporting information on the Web), are often also those that score the most and the least in most other categories. This, however, does not necessarily hold true when looking at options with the second/third, and so on, highest/lowest impact within different categories (color scale in table S10 in the supporting information on the Web). Additionally, when looking at GHG (figure 5a) and other impact categories (figure 6) simultaneously, there is nonetheless little in common when they are analyzed in detail. In fact, GWI chiefly shows the significant role that operational energy savings play and how the embodied impacts are split among the various assemblies and stages of a DSF life cycle. When looking at the other impact categories, operational savings are no longer part of the assessment, and assemblies or stages that were barely noticeable in the GWI (such as maintenance activities, cleaning, and glass disposal) suddenly become worthy of closer attention.

Regarding LCA's role as a tool to enable better informed decisions, the findings of this study provide some interesting insights. In fact, had the decision about which the best/worst DSF options are had been made based merely on GHG impacts, the logical consequence would have been to focus on the

most significant reduction in the operational energy. Still, it was shown that other impact categories suggest a significant impact for other assemblies and stages of a DSF life cycle, such as the production of elements of the outer skin, their maintenance, and disposal—which are also worthy of further investigation. Therefore, our study echoes encouragement for a shift in the current practice of LCA within construction industry. More specifically, the choice of impact categories needs to be revisited and customized to the specifics of each and every case, depending on the context, focus, and purpose of the assessment.

Conclusions

DSFs represent a viable solution to address the refurbishment of existing buildings—an issue pointed out as one of the major opportunities to cut GHG emissions in the construction sector. We assessed the LCEIs of DSFs in refurbishments by two different methods: the GWI, widely used as a single-issue method, and a more comprehensive assessment method (i.e., ReCiPe) to provide a more in-depth understanding of non-GHG impacts. On the one hand, DSFs performed very well when looked at from a GHG impacts perspective and outperformed up-to-standard single skin refurbishments alternatives; we can therefore recommend their broader application to the refurbishment of existing nondomestic buildings in contexts similar to the one we studied, with the aim of mitigating GHG emissions. Nonetheless, when the focus switches to a more comprehensive assessment, the GWI tends to miss out key information that may influence the interpretation of, and conclusions from, the assessment. The neglected impacts do not generally influence the most/least impacting options across different impact categories, but rather how the impacts are spread within each specific category. In the case of the DSFs, our results derived from non-GHG impact categories indicate that more attention should be paid to the support structure of the façade and its maintenance, as well as to more efficient disposal solutions, rather than focusing solely at optimizing DSFs' operational performance, which seems to be where research in the field is mostly headed.

In the complex current scenario of LCA in the construction industry, this article introduces a novel methodological approach for comparative studies that looks at building assemblies and components. Specifically, we have taken into account elements such as the representativeness of the building used, construction practices related to DSFs, industry-informed choices in terms of materials and solutions adopted, a detailed and thorough operational energy analysis, a raw calculation of the potential environmental benefits on a large scale, and—to some extent—indoor comfort, at least in the form of summer overheating.

Although collected data have been input into SimaPro together with their variance, no uncertainty analysis (e.g., by Monte Carlo simulation) has been run and this represents a limitation of this research. Additionally, DSFs can have different structures other than the aluminum one here considered, such as stainless steel trusses or glass fins. In this respect, this

study serves as a proof of concept for a methodology that has been applied to investigate that specific type of DSF. Narrowing down the scope of this research to one specific configuration of DSF has been inevitable to ensure that reasonable and reliable findings could be guaranteed. This can be comprehended as a limit of this study; however, the same methodology can be applied to other configurations to gauge the significance of findings. As such, this represents an interesting area for further research.

Acknowledgments

The authors acknowledge the insights received by the anonymous reviewers. Grateful thanks are also extended to Prof Edgar Hertwich for his valuable input and support.

Notes

- In this article, embodied energy/impacts are defined as those related to all stages other than the use phase (among others, Cabeza et al. 2014; Ibn-Mohammed et al. 2013; Moncaster and Symons 2013). Other researchers (see, e.g., Gustavsson and Joelsson 2010) consider as embodied energy only the energy related to the production and construction phases. We have used the former to provide a more comprehensive approach by incorporating energy and impacts pertaining to decommissioning, dismantling, and disposal stages at the end of the service life of a façade.
- It should be noted that there are researchers persuaded that “in reality, the LCA space is more a continuous spectrum, rather than a dichotomy, between idealised CLCA and ALCA” (Suh and Yang 2014, 1183).
- Often considered the default ReCiPe midpoint method (Dahlstrøm et al. 2012).
- For instance, the replacement of old, single glazing, and metal frame with up-to-standard, double glazing units (DGUs) mounted on thermal-break frames would be exactly the same in both cases, thus representing a quantity that just numerically shifts the results without adding anything to the study.
- More specifically, table S2 in the supporting information on the Web includes data collected for glass cutting and it is followed by data analysis to best choose data inputted into SimaPro. Similarly, table S3 in the supporting information on the Web refers to HST operations also followed by data analysis to determine the best input, whereas tables S5 and S6 in the supporting information on the Web refer to glass edging processes. Table S7 in the supporting information on the Web shows heat transfer coefficients for the elements of the building fabric used in the dynamic thermal simulations. Finally, tables S8 and S9 in the supporting information on the Web are related to data generated with respect to the operational phase.
- An ELCP is constituted of several activities within the same manufacturing plant. If a firm needs to outsource a manufacturing activity for its products, this suddenly becomes another ELCP and the two are linked by transportation (both back and forth if the product then returns to the original plant).
- The pedigree matrix to assess the quality of data sources as per Weidema and colleagues (2013) is given in table S in the supporting information on the Web.
- However, we also wanted to be confident that the buildings modeled can provide comfortable indoor conditions in summer. In this respect, the TM52 method and criteria have been applied (CIBSE 2013a), which specifically aim at preventing overheating in European office buildings. Only a few rooms in a few models resulted in being overheated. Details are given in table S8 in the supporting information on the Web.

References

- Ardente, F., M. Beccali, M. Cellura, and M. Mistretta. 2011. Energy and environmental benefits in public buildings as a result of retrofit actions. *Renewable and Sustainable Energy Reviews* 15(1): 460–470.
- Asdrubali, F., G. Baldinelli, F. D'Alessandro, and F. Scrucca. 2015. Life-cycle assessment of electricity production from renewable energies: Review and results harmonization. *Renewable and Sustainable Energy Reviews* 42: 1113–1122.
- Bala, A., M. Raugei, G. Benveniste, C. Gazulla, and P. Fullana-i-Palmer. 2010. Simplified tools for global warming potential evaluation: When ‘good enough’ is best. *The International Journal of Life Cycle Assessment* 15(5): 489–498.
- Baldinelli, G., F. Asdrubali, C. Baldassarri, F. Bianchi, F. D'Alessandro, S. Schiavoni, and C. Basilicata. 2014. Energy and environmental performance optimization of a wooden window: A holistic approach. *Energy and Buildings* 79: 114–131.
- Bare, J. C., P. Hofstetter, D. W. Pennington, and H. A. U. de Haes. 2000. Midpoints versus endpoints: The sacrifices and benefits. *The International Journal of Life Cycle Assessment* 5(6): 319–326.
- Blengini, G. A. and T. Di Carlo. 2010. The changing role of life-cycle phases, subsystems and materials in the LCA of low energy buildings. *Energy and Buildings* 42(6): 869–880.
- Brunoro, S. 2008. An assessment of energetic efficiency improvement of existing building envelopes in Italy. *Management of Environmental Quality: An International Journal* 19(6): 718–730.
- BSI (British Standards Institution). 2010. BS EN 15643-1:2010. Sustainability of construction works—Sustainability assessment of buildings. Part 1: General framework. London: British Standards Institution.
- BSI (British Standards Institution). 2011. PAS 2050:2011. Specification for the assessment of the life-cycle greenhouse gas emissions of goods and services. London: British Standards Institution.
- Buyle, M., J. Braet, and A. Audenaert. 2013. Life-cycle assessment in the construction sector: A review. *Renewable and Sustainable Energy Reviews* 26: 379–388.
- Cabeza, L. F., L. Rincón, V. Vilariño, G. Pérez, and A. Castell. 2014. Life-cycle assessment (LCA) and life-cycle energy analysis (LCEA) of buildings and the building sector: A review. *Renewable and Sustainable Energy Reviews* 29: 394–416.
- Carbon Trust. 2009. *Building the future, today. Transforming the economic and carbon performance of the buildings we work in*. London: The Carbon Trust.
- Cetiner, I. and E. Ozkan. 2005. An approach for the evaluation of energy and cost efficiency of glass facades. *Energy and Buildings* 37(6): 673–684.
- CIBSE (Chartered Institution of Building Services Engineers). 2008. *CIBSE TM 46: 2008—Energy benchmarks*. London: CIBSE.
- CIBSE (Chartered Institution of Building Services Engineers). 2012. *CIBSE Guide F. Energy efficiency in buildings*. London: CIBSE.

- CIBSE (Chartered Institution of Building Services Engineers). 2013a. *TM 52: 2013—The limits of thermal comfort: Avoiding overheating in European buildings*. London: CIBSE.
- CIBSE (Chartered Institution of Building Services Engineers). 2013b. *CIBSE TM 53: 2013—Refurbishment of non-domestic buildings*. London: CIBSE.
- CIBSE (Chartered Institution of Building Services Engineers) and BSRIA (Building Services Research and Information Association). 2007. *Refurbishment for improved energy efficiency: An overview*. London: CIBSE; Bracknell, UK: BSRIA.
- Collinge, W., A. Landis, A. Jones, L. Schaefer, and M. Bilec. 2013. Dynamic life-cycle assessment: Framework and application to an institutional building. *The International Journal of Life Cycle Assessment* 18(3): 538–552.
- Crawford, R. H. 2009. Life-cycle energy and greenhouse emissions analysis of wind turbines and the effect of size on energy yield. *Renewable and Sustainable Energy Reviews* 13(9): 2653–2660.
- Crawford, R. H. 2011. *Life-cycle assessment in the built environment*. London, New York: Spon.
- Dahlstrøm, O., K. Sørnes, S. T. Eriksen, and E. G. Hertwich. 2012. Life-cycle assessment of a single-family residence built to either conventional- or passive house standard. *Energy and Buildings* 54: 470–479.
- DCLG (Department for Communities and Local Government). 2012a. *Live tables on commercial and industrial floorspace and rateable value statistics*. London: Edited by Department for Communities and Local Government—Her Majesty's Government.
- DCLG (Department for Communities and Local Government). 2012b. *Improving the energy efficiency of buildings and using planning to protect the environment*. London: Edited by Department for Communities and Local Government. First published 7 November 2012—Last updated 16 April 2014—Her Majesty's Government.
- De Benedetti, B., D. Toso, G. L. Baldo, and S. Rollino. 2010. EcoAudit: A renewed simplified procedure to facilitate the environmentally informed material choice orienting the further life-cycle analysis for ecodesigners. *Materials Transactions* 51(5): 832–837.
- de Gracia, A., L. Navarro, A. Castell, D. Boer, and L. F. Cabeza. 2013. Life-cycle assessment of a ventilated facade with PCM in its air chamber. *Solar Energy* 104: 115–123.
- DECC (Department of Energy & Climate Change). 2013a. *Energy consumption in the United Kingdom (ECUK)—User guide*. London: Department of Energy & Climate Change.
- DECC (Department of Energy & Climate Change). 2013b. *Digest of United Kingdom energy statistics 2013*. London: Department of Energy & Climate Change.
- Dixit, M. K., J. L. Fernández-Solís, S. Lavy, and C. H. Culp. 2010. Identification of parameters for embodied energy measurement: A literature review. *Energy and Buildings* 42(8): 1238–1247.
- Dixit, M. K., J. L. Fernández-Solís, S. Lavy, and C. H. Culp. 2012. Need for an embodied energy measurement protocol for buildings: A review paper. *Renewable and Sustainable Energy Reviews* 16(6): 3730–3743.
- EEBPP (Energy Efficiency Best Practice Program). 2000. *Energy use in offices*. London: Energy Efficiency Best Practice Program.
- Eldh, P. and J. Johansson. 2006. Weighting in LCA based on ecotaxes—Development of a mid-point method and experiences from case studies. *The International Journal of Life Cycle Assessment* 11(1): 81–88.
- Erlandsson, M. and M. Borg. 2003. Generic LCA-methodology applicable for buildings, constructions and operation services—Today practice and development needs. *Building and Environment* 38(7): 919–938.
- Ferreira, J., M. D. Pinheiro, and J. de Brito. 2013. Refurbishment decision support tools review—Energy and life-cycle as key aspects to sustainable refurbishment projects. *Energy Policy* 62: 1453–1460.
- Finnveden, G., M. Z. Hauschild, T. Ekvall, J. Guinee, R. Heijungs, S. Hellweg, A. Koehler, D. Pennington, and S. Suh. 2009. Recent developments in life-cycle assessment. *Journal of Environmental Management* 91(1): 1–21.
- Gakovic, B. 2000. Areas and types of glazing and other openings in the nondomestic building stock. *Environment and Planning B: Planning and Design* 27(5): 667–694.
- Gissen, D. 2005. Breathing room: Arup's new London headquarters celebrates its mechanical systems. *Architectural Record* 193(7): 163–164.
- Goedkoop, M., R. Heijungs, M. A. J. Huijbregts, A. De Schryver, J. Struijs, and R. van Zelm. 2013. *ReCiPe 2008. A life-cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. First edition (version 1.08)*. The Hague, the Netherlands: Netherlands Ministry of Infrastructure and the Environment.
- Gratia, E. and A. De Herde. 2007. Are energy consumptions decreased with the addition of a double-skin? *Energy and Buildings* 39(5): 605–619.
- Guinée, J. B., R. Heijungs, G. Huppes, A. Zamagni, P. Masoni, R. Buonomici, T. Ekvall, and T. Rydberg. 2011. Life-cycle assessment: Past, present, and future. *Environmental Science & Technology* 45(1): 90–96.
- Gustavsson, L. and A. Joelsson. 2010. Life-cycle primary energy analysis of residential buildings. *Energy and Buildings* 42(2): 210–220.
- Hammond, G. and C. Jones. 2011. *Embodied carbon: The inventory of carbon and energy (ICE)*. BG 10/2011. Bath, UK: University of Bath; Bracknell, UK: BSRIA.
- Hammond, G. P. and C. I. Jones. 2008. Embodied energy and carbon in construction materials. In *Proceedings of the ICE—Energy* 161(2): 87.
- Heijungs, R., G. Huppes, and J. Guinée. 2009. *A scientific framework for LCA*. Leiden, the Netherlands: CML-Leiden University.
- Hill, N., H. Walker, J. Beevor, and K. James. 2011. *Guidelines to Defra/DECC's GHG conversion factors for company reporting: Methodology paper for emission factors*. Department for Environment, Food and Rural Affairs (DEFRA) and Department of Energy and Climate Change (DECC). London: DEFRA.
- Ibn-Mohammed, T., R. Greenough, S. Taylor, L. Ozawa-Meida, and A. Acquaye. 2013. Operational vs. embodied emissions in buildings—A review of current trends. *Energy and Buildings* 66: 232–245.
- IEA (International Energy Agency). 2014. *Technology roadmap. Energy efficient building envelopes*. Paris: International Energy Agency.
- IES (Integrated Environmental Solutions). 2009. *Building energy and environmental modelling; Checklist for choosing BEEM software*. ApacheSim. Glasgow, UK: IES.
- IES (Integrated Environmental Solutions). 2012. *MacroFlo calculation methods. Technical manual*. Glasgow, UK: IES.
- Ip, K. and A. Miller. 2012. Life-cycle greenhouse gas emissions of hemp-lime wall constructions in the UK. *Resources, Conservation and Recycling* 69: 1–9.
- IPCC (Intergovernmental Panel on Climate Change). 2013. Working Group I Contribution to the Fifth Assessment Report of the

- Intergovernmental Panel on Climate Change. *Climate Change 2013—The physical science basis*, edited by T. F. Stocker et al. Cambridge, UK; New York: Cambridge University Press.
- ISO (International Organization for Standardization). 2006a. *BSI EN ISO 14044:2006 Environmental management—Life-cycle assessment—Requirement and guidelines*. London: British Standards Institution.
- ISO (International Organization for Standardization). 2006b. *BSI EN ISO 14040:2006 Environmental management—Life-cycle assessment—Principles and framework*. London: British Standards Institution.
- Jin, Q. and M. Overend. 2014. A prototype whole-life value optimization tool for façade design. *Journal of Building Performance Simulation* 7: 217–232.
- Kellenberger, D. and H.-J. Althaus. 2009. Relevance of simplifications in LCA of building components. *Building and Environment* 44(4): 818–825.
- Kim, G., L. A. Schaefer, and J. T. Kim. 2013. Development of a double-skin facade for sustainable renovation of old residential buildings. *Indoor and Built Environment* 22(1): 180–190.
- Kolokotroni, M., S. Robinson-Gayle, S. Tanno, and A. Cripps. 2004. Environmental impact analysis for typical office facades. *Building Research & Information* 32(1): 2–16.
- LCICG (Low Carbon Innovation Coordination Group). 2012. *Non-domestic buildings summary report*. London: Department of Energy & Climate Change and Carbon Trust.
- Malmqvist, T., M. Glaumann, S. Scarpellini, I. Zabalza, A. Aranda, E. Llera, and S. Diaz. 2011. Life-cycle assessment in buildings: The ENSLIC simplified method and guidelines. *Energy* 36(4): 1900–1907.
- Monahan, J. and J. C. Powell. 2011. An embodied carbon and energy analysis of modern methods of construction in housing: A case study using a lifecycle assessment framework. *Energy and Buildings* 43(1): 179–188.
- Moncaster, A. M. and J. Y. Song. 2012. A comparative review of existing data and methodologies for calculating embodied energy and carbon of buildings. *International Journal of Sustainable Building Technology and Urban Development* 3(1): 26–36.
- Moncaster, A. M. and K. E. Symons. 2013. A method and tool for ‘cradle to grave’ embodied carbon and energy impacts of UK buildings in compliance with the new TC350 standards. *Energy and Buildings* 66(1): 514–523.
- Nicolae, B. and B. George-Vlad. 2015. Life-cycle analysis in refurbishment of the buildings as intervention practices in energy saving. *Energy and Buildings* 86: 74–85.
- Oesterle, E., R. Lieb, M. Lutz, and W. Heusler. 2001. *Double-skin facades. Integrated planning*. Munich, London, New York: Prestel.
- Pauliuk, S., K. Sjöstrand, and D. B. Müller. 2013. Transforming the Norwegian dwelling stock to reach the 2 degrees Celsius climate target. *Journal of Industrial Ecology* 17(4): 542–554.
- Peereboom, E. C., R. Kleijn, S. Lemkowitz, and S. Lundie. 1998. Influence of inventory data sets on life-cycle assessment results: A case study on PVC. *Journal of Industrial Ecology* 2(3): 109–130.
- Pérez-Lombard, L., J. Ortiz, and C. Pout. 2008. A review on buildings energy consumption information. *Energy and Buildings* 40(3): 394–398.
- Poirazis, H. and M. Kragh. 2009. Establishing a simplified correlation between a proposed double skin facade and a thermally equivalent single skin facade for dynamic building energy modelling. In *11th International IBPSA Conference*. 27–30 July, Glasgow, Scotland.
- Pomponi, F., K. Ip, and P. Piroozfar. 2013. Assessment of double skin facade technologies for office refurbishments in the United Kingdom. Paper presented at *SB13 Conference. Sustainable Buildings—Construction Products & Technologies*, 25–28 September, Graz, Austria.
- PRÉ Consultants. 2000. *The Eco-Indicator 99. A damage oriented method for life cycle impact assessment*. Methodology report and manual for designers. Technical report. Amersfoort, the Netherlands: PRÉ Consultants.
- Radhi, H. and S. Sharples. 2013. Global warming implications of facade parameters: A life-cycle assessment of residential buildings in Bahrain. *Environmental Impact Assessment Review* 38: 99–108.
- Reap, J., F. Roman, S. Duncan, and B. Bras. 2008. A survey of unresolved problems in life-cycle assessment. *The International Journal of Life Cycle Assessment* 13(5): 374–388.
- Scheuer, C., G. A. Keoleian, and P. Reppe. 2003. Life-cycle energy and environmental performance of a new university building: Modeling challenges and design implications. *Energy and Buildings* 35(10): 1049–1064.
- Shahrestani, M., R. Yao, and G. K. Cook. 2013. A review of existing building benchmarks and the development of a set of reference office buildings for England and Wales. *Intelligent Buildings International* 6(1): 41–64.
- Shameri, M. A., M. A. Alghoul, K. Sopian, M. F. M. Zain, and O. Elayeb. 2011. Perspectives of double skin facade systems in buildings and energy saving. *Renewable & Sustainable Energy Reviews* 15(3): 1468–1475.
- Steadman, P., H. R. Bruhns, S. Holtier, B. Gakovic, P. A. Rickaby, and F. E. Brown. 2000. A classification of built forms. *Environment and Planning B: Planning and Design* 27(1): 73–91.
- Stevenson, F. 2013. Reducing energy demand through retrofitting buildings. *Building Research & Information* 41(5): 605–608.
- Suh, S. and Y. Yang. 2014. On the uncanny capabilities of consequential LCA. *The International Journal of Life Cycle Assessment* 19(6): 1179–1184.
- Tandy, B. C. and A. Way. 2004. R&D to improve site practices for collection and clean separation of composite (glass) material in the construction and demolition industry—R&D report: Glass. Banbury, UK: The Waste & Resources Action Programme (WRAP).
- Tellnes, L. G. F., L. R. Gobakken, P. O. Flæte, and G. Alfreksen. 2014. Carbon footprint including effect of carbon storage for selected wooden facade materials. *Wood Material Science & Engineering* 9(3): 139–143.
- Thomas, L. 2010. Evaluating design strategies, performance and occupant satisfaction: A low carbon office refurbishment. *Building Research & Information: The International Journal of Research, Development and Demonstration* 38(6): 610–624.
- Turconi, R., A. Boldrin, and T. Astrup. 2013. Life-cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations. *Renewable and Sustainable Energy Reviews* 28: 555–565.
- Wadel, G., P. Alonso, J.-L. Zamora, and P. Garrido. 2013. Simplified LCA in skin design: The FB720 case. *International Journal of Sustainable Building Technology and Urban Development* 4(1): 68–81.
- Weidema, B. P., M. Thrane, P. Christensen, J. Schmidt, and S. Løkke. 2008. Carbon footprint: A catalyst for life-cycle assessment? *Journal of Industrial Ecology* 12(1): 3–6.
- Weidema, B. P., C. Bauer, R. Hischier, C. Mutel, T. Nemecek, J. Reinhard, C. O. Vadenbo, and G. Wernet. 2013. *Overview and methodology. Data quality guideline for the Ecoinvent database version*

3. *Ecoinvent report 1 (v3)*. St. Gallen, Switzerland: The ecoinvent Center: Swiss Center for Life Cycle Inventories.
- Zabalza Bribián, I., A. Aranda Usón, and S. Scarpellini. 2009. Life-cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification. *Building and Environment* 44(12): 2510–2520.
- Zamagni, A., P. Buttol, P. Porta, R. Buonomici, P. Masoni, J. Guinée, R. Heijungs, T. Ekvall, R. Bersani, and A. Bienkowska. 2008. *Critical review of the current research needs and limitations related to ISO-LCA practice*. Rome: ENEA, The Italian National Agency on New Technologies, Energy and the Environment.

About the Authors

Francesco Pomponi is a Research Associate at the University of Cambridge in Cambridge, UK. **Poorang Piroozfar** is an architect, director of @BEACON research center, and the architectural technology program leader in the School of Environment and Technology, University of Brighton, Brighton, UK. **Eric R.P. Farr** is a professional educator, an independent researcher, and critic who has been a senior architectural/urban design consultant and urban planning strategist for more than 15 years in San Diego, CA, USA.

Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web site:

Supporting Information S1: This supporting information includes information about pedigree matrix for data quality; primary data collected for flat glass cutting, heat soak test, flat glass edging, and other primary data; details of the simulated building model; corrections for flow in cavities; operational energy results; operational embodied global warming potential (GWP) figures; and life cycle impact assessment results. It includes ten tables and three figures.