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Double Skin Façades for the Sustainable Refurbishment of Non-Domestic Buildings: A Life Cycle Environmental Impact Perspective

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Abstract (Maximum 300 words)

In developed countries, existing buildings have the biggest share in the building stock. Given the age of construction, the property vs. land values, and their slow replacement rate, low-carbon refurbishments are arguably one of the most sensible ways to mitigate environmental impacts (EIs) in the construction sector and meet the greenhouse gas (GHG) reduction targets. In this respect, Double Skin Façade (DSF) has been defined as one of the most effective ways to efficiently manage interactions between outdoors and indoors, and its benefits span from passive heating and cooling to the enhancement of thermal comfort of the occupied spaces. A plethora of research does exist on the operational behaviour of the DSF. However, life cycle energy figures and EIs are yet to be established fully and comprehensively. This paper reports on findings of an on-going research project aimed at filling such a gap. More specifically, life cycle assessment (LCA) and building energy modelling (BEM) have been combined to build a methodology to help assess life cycle energy figures in a more holistic manner. Primary data has been collected from manufacturers from across Europe about all the life cycle stages and processes related to a DSF refurbishment. Results show that if on the one hand the life cycle energy balance actually is negative, hence supporting a wider adoption of DSFs in refurbishments, on the other hand there exists ecological and EIs that the DSF bears; what cannot be easily overlooked if a more responsive approach to the EIs is to be undertaken. Not only do these findings inform a more energy-efficient deployment of DSFs, but they also highlight the need for a more holistic and impacts-driven design approach to ensure that the environmental burdens are not just shifted from one impact category to another.

INTRODUCTION

In countries like the UK, the existing buildings stock is where the greatest opportunities for improvement lie, and reducing energy demand through retrofitting deserves to become a priority (Stevenson, 2013). It is expected that by 2050, 75%-90% of the existing buildings will still be standing and their upkeep is one of the major challenges to achieve the carbon reduction targets (IEA, 2014).

Given this context, improvements to buildings' façades can arguably be amongst the most effective interventions from a sustainability point of view. More specifically, glazed Double Skin Façades (DSFs) are among the best façade technologies to reduce energy consumption and greenhouse gas (GHG) emissions, while helping provide comfortable conditions to the occupied spaces (Shameri et al., 2011). In refurbishments, a DSF consists of a second, glazed skin installed in front of the existing building façade, which creates an air space that acts either as a thermal buffer or a ventilation channel or a combination of both. Operational behaviour of the DSF has been widely studied and, in temperate climates, this technology promises significant reductions of 30%-60% in heating and cooling loads (e.g. Gratia and De Herde, 2007, Cetiner and Ozkan, 2005). To the contrary, existing knowledge is extremely limited about DSF embodied energy (EE), embodied carbon (EC) and life cycle environmental impacts (LCEIs).

This paper aims to address such a knowledge gap through a comparative assessment of DSFs and up-to-standards single skin (SS) refurbishments solutions. Specifically, the LCEIs of DSFs for office refurbishments are assessed through a cradle-to-grave LCA with a twofold aim. Firstly, Cumulative Energy Demand (CED) and Global Warming Potential (GWP) are used as impact assessment methods to answer the following research question: can DSFs be considered as a low-carbon refurbishment solution for the UK? Secondly, a more comprehensive impact assessment method, i.e. ReCiPe, is used to reveal what additional impacts the DSF bears despite its energy and carbon saving potential.

LCA IN THE ARCHITECTURE ENGINEERING AND CONSTRUCTION (AEC) 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, little clarity in the functional unit (FU) considered, diverse methodologies and methods for conducting the studies, and the focus mainly on real buildings 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 dimensions. Additionally, the long lifespan of buildings combined with the change of use during their service life imply lower predictability and higher uncertainty of variables, parameters, and future scenarios. Such difficulties eventually lead to taking a 'reductionist' approach in many recent LCAs, where the term ‘simplified’ often recurs (Bala et al., 2010, De Benedetti et al., 2010, Malmqvist et al., 2011, Wadel et al., 2013, Zabalza Bribián 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 GWP as the assessment method when analysing impacts of buildings and their components from a life cycle perspective (Ardente et al., 2011, Hammond and Jones, 2008, Pauliuk et al., 2013). The emphasis on the use of GWP as a method to assess GHG emissions has been described as a crude approach but also beneficial to ease understanding and enhance transparency (Weidema et al., 2008). Nevertheless, GWP fails to account for important impacts (Asdrubali et al., 2015) such as eco- and human-toxicity, or water and land use, and may lead to erroneous judgments about environmental consequences (Turconi et al., 2013).

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 (EIs) that are not only difficult to track but also challenging to assess and interpret (Dixit et al., 2012). Therefore, when considering LCA as a facilitator to help determine the least damaging alternative, the adoption of more comprehensive impact assessment methods combined with life cycle energy and carbon assessments is arguably a sensible way forward.

LCAs of DSFs

Only two studies exist where DSFs have been examined in detail from a life cycle perspective (de Gracia et al., 2013, Wadel et al., 2013). This alone represents a gap in knowledge with reference to a technology widely used in the AEC industry with a strong belief that it delivers “green” buildings, and is thus able to reduce EIs. Furthermore, both studies refer to specific façade typologies, located in well-defined and particular contexts, thus increasing the difficulty in comparing and replicating results and methodologies. Additionally, both the DSFs considered in the studies are innovative products which do not represent the current practice in the AEC industry.

Wadel et al. (2013) adopt a *simplified* LCA for an innovative type of DSF with vertical shading devices placed at specific intervals. The use phase is not incorporated in the LCA and impacts assessed throughout the study are limited to embodied energy and CO_2 emissions, the FU being 1 m^2 of the façade with a lifespan of 50 years. With reference to those two impact categories the DSF, in its best configuration, is capable of a 50% reduction in energy consumption and CO_2 emissions, compared to conventional façades (Wadel et al., 2013).

At an even more specific level, de Gracia et al. (2013) conduct a cradle-to-grave LCA of a DSF with phase change materials (PCM) in its cavity. They utilise the Eco-Indicator 99 (EI99), an impact assessment method based on endpoints. This means that results from different impact categories are normalised and brought together to contribute to a final, single, cumulative score (known as the ‘endpoint’) for the product/process under examination. The FUs used are two cubicles constructed in Spain, one with the DSF, the other without, with a lifespan of 50 years; the former reduces the EI by 7.5% compared to the reference case (de Gracia et al., 2013).

Notwithstanding the importance of regional and local foci in LCAs, neither study allows for the generalisations needed for better informed applications of DSFs. 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 EI assessment of office façades has been done by Kolokotroni et al. (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 authors 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 but the lowest EI99 score.

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 SS solutions. Consequently, primary data related to DSFs are still largely missing in the literature. In other words, the LCEIs of DSFs are yet to be established comprehensively. This is mainly due to a lack of data for glass processes, and echoes a known issue in the LCA community: the lack of reliable and complete data about buildings materials and assemblies which, if they existed, would allow for greater environmental benefits (Crawford, 2009, Reap et al., 2008).

RESEARCH METHODOLOGY AND METHODS

For this research, a cradle-to-grave LCA has been conducted based on the aforementioned TC350 standards. Specifically, a clear distinction is considered between the thermal behaviour of the building, i.e. the energy analysis of the DSF models, and the embodied impacts in pre- and post-occupancy phases, and end of life stages. These will be addressed in the next two subsections, followed by details for the EIs assessment.

Operational phase

Yearly operational energy consumption for space heating in both single- and double-skin models has been simulated through IES VE, a building energy simulation (BES) software used by academics and practitioners alike, and successfully deployed in DSF studies (e.g. Kim et al., 2013).

Table 1 - Full details of dynamic thermal simulations

Element of the building fabric	Corresponding U-value	Parameter	Value
		Heating & occupancy profile	ASHRAE 8am-6pm M-F
		Heating set point/system	19.5 °C /radiators
		Internal gains	21.5 W/m²
Roof	0.18 W/m² K	Max sensible people gain	73.2 W/person
Ground floor	0.22 W/m² K	Occupancy density	13.93 m²/person
External walls	0.26 W/m² K	Infiltration max flowrate	0.167 ach
External windows	1.60 W/m² K	External windows open at	22 °C
DSF glazing	4.62 W/m² K	Cavity opens at	15 °C or 20 °C out. temp

IES includes a natural ventilation analysis module which addresses phenomena such as single-sided and cross-ventilation, and flow in cavities due to wind and buoyancy effects. Additionally, elements such as infiltration and thermal mass are also suitably dealt with (IES, 2009). The DSF structure obstructs to some extent the flow in the cavity, and the software vendor recommends correction in such cases, which have then been applied (IES, 2014). Full details for the replicability of the study are given in Table 1. Reviewed LCA literature has shown that studies are often based on specific buildings, thus hindering generalisation of the conclusions and comparability of the results. Therefore, a generic yet representative office (Figure 1 left) with a very slender built form has been selected; which is the most common office building type in England (Shahrestani et al., 2013, Steadman et al., 2000).

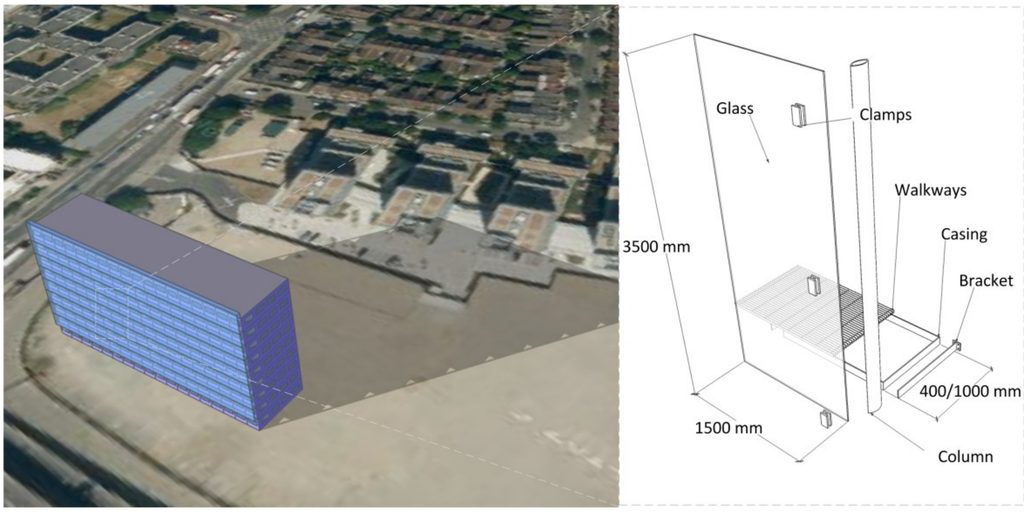

Figure 1 - Office building model (left) and exploded view of the FU (right)

It is assumed an open plan layout of the internal spaces after the refurbishment. The building is located in London (weather file: Heathrow EWY). It consists of 9 floors of 66.6 m x 16 m, totalling 9590 m^2 of treated floor area (TFA). Window to wall ratio (WWR) equals to 0.25 which is a typical and highly correlated value to offices of this type (Gakovic, 2000). The building is naturally ventilated, as are the majority of existing offices in the UK (CIBSE, 2013). The façade service life is assumed at 25 years in line with studies specifically focused on building façades in the UK (Jin and Overend, 2013). The DSF is equipped with a basic form of Building Management System (BMS) that opens the bottom and the top of the cavity when either outside air temperature exceeds 20 °C or cavity temperature exceeds 15 °C. These values are the result of an optimisation process aimed at minimising overheating of the indoor spaces in summer.

Embodied impacts

DSFs are defined by several parameters, including the geometry of the cavity and its width. The configuration chosen here is multi-story, consisting of a cavity with no horizontal or vertical partitions. Regarding cavity width, narrow and wide categories are widely acknowledged and both are considered. Geometry of the building, data collected from visits to construction glass manufacturing facilities, interviews with a leading façade engineering and manufacturing company, and the construction specifications, all helped determine the FU

– which is 5.25 m² of façade (Figure 1 right) – and the choice of additional parameters, leading to the options in Table 2. The combination of the parameters in Table 2 leads to a total of 128 assessed options. Furthermore, eight additional SS scenarios (one for each orientation) were also realised and assessed in order to allow operational energy comparisons.

Table 2 - Realised and assessed options

Parameter	Options assessed	Code(s)	No.	Details
Cavity	Narrow Wide	CN CW	2	400 mm wide 1000 mm wide
Glass composition	Monolithic Laminated	M L	2	12 mm thermally toughened (TT) – Heat 8mm TT + 8mm TT + 1.52 mm PVB
Glass coating	Clear Coated	CL CO	2	Clear Float Glass Solar Control Glass
Structure Manufacture	Central Europe China	Eu Int	2	Lorry Euro 4 (500 km) Transoceanic ship (20070 km) - Train (140
Orientation	All combinations with 45° step	E, NE, N, W, SW, S,	8	

Current regulations mandate that operations needed for a SS 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. In doing so, this study accounts for the surplus of materials and processes involved when double-skin façade refurbishment is compared to single-façade. These are represented in Figure 2 which shows the flowchart for the FU and its system boundaries.

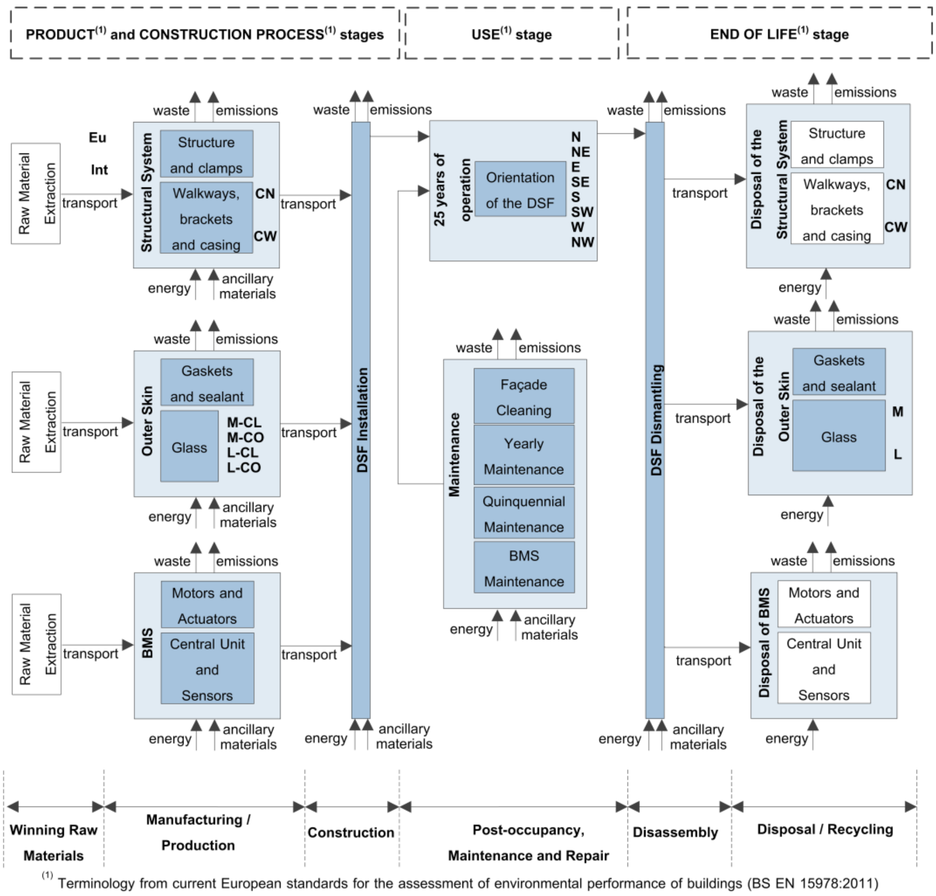

Figure 2 - Flowchart for the FU and its system boundaries

Data collection has been conducted systematically starting from the macro-assemblies as shown in Figure 2 through a process-based analysis that refers to a mix of processes, products, and location-specific data to calculate and establish the EI of a product system. 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. White boxes in Figure 2 indicate assemblies and stages for which EcoInvent data have been used. End of life treatments, i.e. recycling/waste figures, have been modelled according to the waste/recycling scenario available for England in EcoInvent.

Environmental impacts assessment

Attributional LCA (ALCA) and consequential LCA (CLCA) are known to be the main two methodological approaches commonly used by the LCA community. Due to the specific focus of this research on DSFs as a product, ALCA is the approach chosen for its focus on physical flows to and from a life cycle and its components. It is also recommended in the British Standard, PAS 2050:2011, 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, the most widely used LCA software, is the tool adopted for this study.

As aforementioned, two different impact assessment methods have been used to assess the low-carbon potential of the DSF: the CED (Frischknecht et al., 2003) and the GWP over a 100-year horizon (IPCC, 2013). Additionally, ReCiPe hierarchic perspective midpoint v1.10 (Goedkoop et al., 2013)—which is a multi-category method commonly used in LCAs—has been used to assess additional ecological and EIs other from climate change. Midpoint modelling allows for higher transparency and lower uncertainty, whereas endpoint modelling shows things with more relevance but can be less transparent and harder to compare (Blengini and Di Carlo, 2010). Due to the unavailability of data for DSFs, midpoint modelling with an aim at maximising transparency was chosen.

RESULTS

Figure 3 and Figure 4 show energy and carbon results respectively for the assessed scenarios. More specifically, 16 data series are presented that describe unique combinations of the DSF parameters considered. Each of them includes 8 data points that refer to the different orientation of the building with that specific DSF configuration, thus totalling 128 data points. Dashed lines are indifference curves: data points below those lines have a negative life cycle balance (positive outcome).

As Figure 3 shows, life cycle energy results are very promising with 120 out of 128 options (93.75%) showing a negative life energy balance. The eight options with a pejorative life cycle energy balance are all characterised by a wide cavity and a SE orientation. Successful options drop to 72.65% (93 out of 128) when the focus switches to carbon (Figure 4).

This is due to the actual source of energy that is being saved by the DSF (natural gas for space heating) vs. the source of energy needed for the augmented embodied impacts of the

DSF (mainly mid-voltage electricity for manufacturing activity). More specifically, gas and electricity have different GHG conversion factors (i.e. 1 kWh $_{GAS}$ = 0.20155 $kgCO_{2e}$; 1 kWh $_{ELEC}$ = 0.59368 $kgCO_{2e}$) thereby shifting options with a negative life cycle energy balance into options with a positive (pejorative effect) life cycle carbon balance. Among the options with a pejorative effect only two have a narrow cavity and both are SE oriented models.

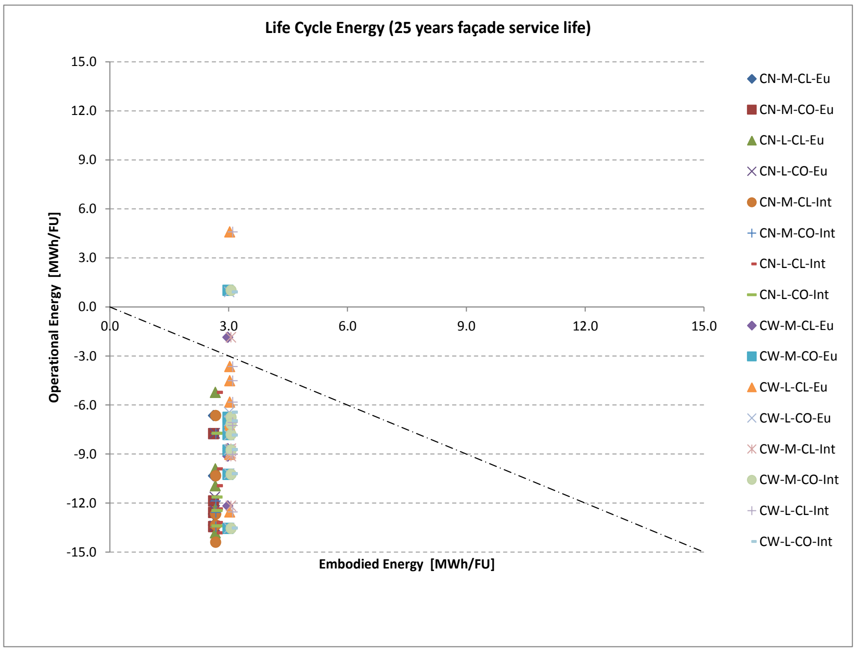

Figure 3 – Life cycle energy results (for abbreviations please refer to Table 2)

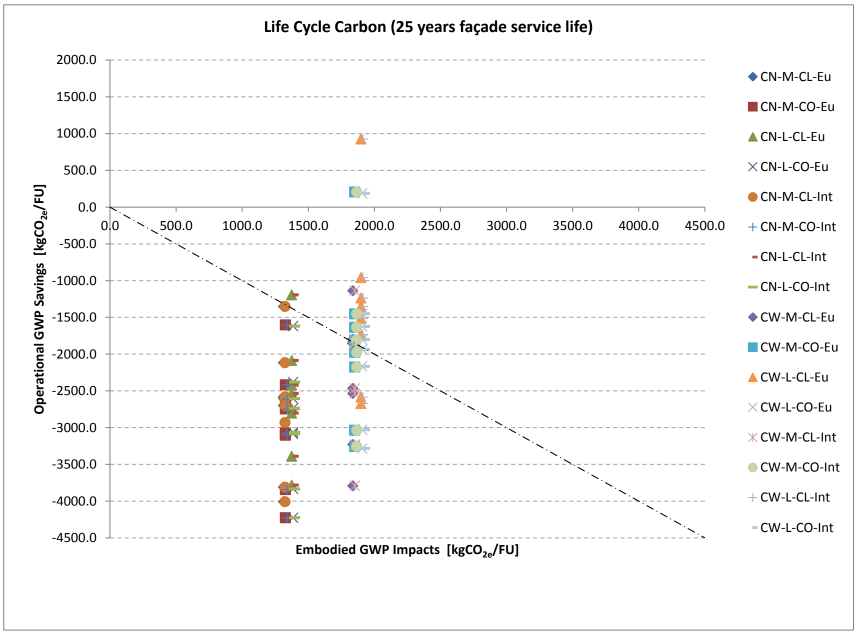

Figure 4 - Life cycle carbon results (for abbreviations please refer to Table 2)

Table 3 shows the EI assessment results from ReCiPe with a colour scale to indicate highest/lowest impact within different categories. Orientation of the building models is omitted since it does not influence the embodied environmental and ecological impacts.

In the results from ReCiPe, operational savings are no longer significant. By contrast, assemblies and stages of the DSF show their embodied impacts that suddenly become worthy of closer attention.

Table 3 - ReCiPe results (green= lowest impact; red=highest impact)

Options	IMPACT CATEGORIES (IC) - ReCiPe hierarchic perspective midpoint v1.10																	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
CN-M-CL-Eu	1312.83	91.69	7.46	561.38	0.39	672.14	6.34	3.35	0.11	27.10	25.25	161.95	13.59	5.16	2.3E-02	10065.97	151.48	184.4
CN-M-CL-Int	1324.88	92.39	7.74	561.57	0.40	672.45	6.56	3.44	0.11	27.11	25.29	162.75	13.60	5.16	2.3E-02	10067.97	151.48	188.9
CN-M-CO-Eu	1326.98	92.81	7.55	569.95	0.40	677.37	6.41	3.38	0.12	27.15	25.30	168.53	13.87	5.19	2.3E-02	10142.96	151.48	184.4
CN-M-CO-Int	1339.03	93.51	7.84	570.15	0.40	677.68	6.63	3.47	0.12	27.15	25.34	169.33	13.88	5.19	2.3E-02	10144.95	151.48	188.9
CN-L-CL-Eu	1374.58	92.94	7.63	575.10	0.40	692.58	6.52	3.41	0.13	27.52	25.66	174.77	17.32	5.37	2.2E-02	10170.86	151.58	186.7
CN-L-CL-Int	1386.63	93.64	7.91	575.30	0.41	692.88	6.74	3.49	0.13	27.52	25.70	175.57	17.34	5.37	2.2E-02	10172.85	151.58	191.2
CN-L-CO-Eu	1384.56	94.02	7.73	584.59	0.41	687.71	6.60	3.44	0.12	27.45	25.60	181.22	17.24	5.35	1.5E-02	10253.57	151.56	185.7
CN-L-CO-Int	1396.61	94.71	8.01	584.79	0.41	688.02	6.82	3.53	0.12	27.46	25.65	182.02	17.25	5.35	1.5E-02	10255.56	151.56	190.2
CW-M-CL-Eu	1836.73	126.86	9.12	752.67	0.58	923.97	7.45	4.55	0.17	42.64	39.30	251.22	16.34	7.14	2.2E-02	16993.65	204.56	198.5
CW-M-CL-Int	1853.28	127.85	9.50	752.95	0.59	924.39	7.75	4.67	0.17	42.65	39.36	252.31	16.36	7.14	2.2E-02	16996.37	204.56	204.5
CW-M-CO-Eu	1850.88	127.98	9.21	761.25	0.59	929.20	7.52	4.58	0.17	42.68	39.35	257.80	16.63	7.17	2.2E-02	17070.63	204.56	198.5
CW-M-CO-Int	1867.43	128.98	9.59	761.52	0.60	929.62	7.82	4.70	0.17	42.69	39.40	258.88	16.64	7.17	2.2E-02	17073.36	204.56	204.6
CW-L-CL-Eu	1898.48	128.11	9.29	766.40	0.59	944.40	7.64	4.61	0.19	43.05	39.71	264.04	20.08	7.34	2.1E-02	17098.53	204.66	200.8
CW-L-CL-Int	1915.04	129.11	9.67	766.67	0.60	944.82	7.94	4.73	0.19	43.06	39.77	265.12	20.10	7.35	2.1E-02	17101.26	204.66	206.8
CW-L-CO-Eu	1908.46	129.18	9.38	775.89	0.60	939.53	7.71	4.64	0.18	42.99	39.66	270.49	20.00	7.33	1.4E-02	17181.24	204.64	199.8
CW-L-CO-Int	1925.02	130.18	9.76	776.16	0.61	939.96	8.01	4.76	0.18	43.00	39.71	271.58	20.01	7.33	1.4E-02	17183.97	204.64	205.8

ICs: 1=Climate Change [kg CO_{2eq}]; 2=Ozone depletion [mg CFC-11_{eq}]; 3=Terrestrial acidification [kg SO_{2eq}]; 4=Freshwater eutrophication [g P_{eq}]; 5=Marine eutrophication [kg N_{eq}]; 6=Human toxicity [kg 1,4-DB_{eq}]; 7=Photochemical oxidant formation [kg NMVOC]; 8=Particulate matter formation [kg PM_{10eq}]; 9=Terrestrial ecotoxicity [kg 1,4-DB_{eq}]; 10=Freshwater ecotoxicity [kg 1,4-DB_{eq}]; 11=Marine ecotoxicity [kg 1,4-DB_{eq}]; 12=Ionising radiation [kBq $U235_{eq}$]; 13=Agricultural land occupation [m^2a]; 14=Urban land occupation [m^2a]; 15=Natural land transformation [m^2]; 16=Water depletion [m^3]; 17=Metal depletion [kg Fe_{eq}]; 18=Fossil depletion [kg oil_{eq}]

DISCUSSION OF FINDINGS

With respect to the research question that this study aims answering, i.e. can DSFs be considered as a low-carbon refurbishment solution for the UK?, results have shown that for the vast majority of the options assessed DSFs perform extremely well when looked at from a life cycle perspective. More specifically, 93.75% and 72.65% of the options performed better than their SS counterparts in terms of life cycle energy and carbon, respectively. DSFs application to the refurbishment of existing non-domestic buildings therefore, can be recommended in the contexts similar to the one studied here, with the aim of mitigating GHG emissions.

The parametric approach adopted in this study allows for some significant insights in terms of sensitivity analysis regarding the options that showed a positive life cycle balance (negative outcome). Cavity width and orientation are, in such order, the most significant parameters both energy- and carbon-wise. Wider cavities imply a higher amount of construction materials to be manufactured, transported, installed, and disposed of, thereby increasing significantly both embodied energy and carbon. Wider cavities also imply a higher mass of air that needs to be solar-heated prior to 'activating' the thermal buffer behaviour of the DSF. Such an aspect explains why narrow cavities show slightly better operational energy savings.

Regarding the orientation, SE is the common underlying characteristics of most of the unsuccessful options. A SE oriented building can benefit from a fair amount of solar gain and, in fact, the SE oriented SS model is the one with the least energy consumption amongst the eight SS options. In the DSF model, the solar gain increases the temperature of air in the cavity that eventually reaches the threshold which activates openings at the bottom and the top through the BMS. Therefore, for the majority of the occupied time the cavity is open and its thermal buffer effect is almost counteracted, and so is its energy saving potential.

Glass type and glass coating, in such order, follow in terms of significance, with monolithic glass to be preferred over laminated glass, and clear glass over coated glass. When looking at the two parameters combined, their significance implies that M-CO options are always better than L-CL options (glass type predominant over glass coating). Source of the materials is the least impacting parameter, with EU sourced materials showing lower impacts than those coming from China.

In contextualising our results with the only LCA of DSFs that provides sufficient detail to attempt a comparison (Wadel et al., 2013), specific values are in line energy-wise whereas there exists a big difference for what concerns carbon. Specifically, the embodied energy of the 128 options we assessed ranges from 1793.11 MJ/m² to 2127.93 MJ/m², which are values significantly close to the 2273.08 MJ/m² of Wadel et al. (2013). To the contrary, their embodied carbon equals to 178.64 kg CO_{2e}/m² whereas we found a range of 250.06 – 366.67 kg CO_{2e}/m² which is up to more than twice as much. A possible reason lies in the significant amount of primary data we collected from manufacturers that allowed us to assess embodied figures with less uncertainty and fewer assumptions. However, the DSF assessed by Wadel et al. (2013) represents an innovative system made out of recycled materials that does not constitute current and common practice in the AEC sector; therefore it cannot be used as a broad basis for comparison.

Regarding the ReCiPe results (Table 3), the options with the highest and lowest impact categories, identified with reference to the GWP, i.e. climate change, are often also those which 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 etc. highest/lowest impact within different categories (colour scale in Table 3). Additionally, there is nonetheless little in common when the impacts are analysed in detail. In fact, had the decision about which the best/worst DSF options are had been made based merely on life cycle energy and carbon balances, the logical consequence would have been to focus on the most significant reduction in those. Still, it was shown that other impact categories suggest also significant impacts 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 worthy of further investigation. Therefore, our study echoes encouragement for a shift in the current practice of LCA within the construction industry. More specifically, the choice of impact categories needs to be revisited and customised to the specifics of each and every case, depending on the context, focus and purpose of the assessment.

CONCLUSIONS

This study has shown that the vast majority of the DSF options assessed perform better than their SS counterparts when used in office refurbishments in the UK. The combined use of life cycle energy and carbon assessments not only showed how significant the energy reduction potential is but it also indicated which options are critical when the focus switches to carbon, thus taking into account the specific type of energy that is being saved. Additionally, the use of ReCiPe as a multi-category impact assessment method highlighted that energy and carbon analyses tend to miss out key information that may influence the interpretation of, and conclusions from, the assessment. In the case of DSFs, ReCiPe results indicate that more attention should be paid to the structure of the façade and its maintenance, and to more efficient disposal solutions, rather than focusing solely at optimising DSFs' operational performance, which seems to be where research in the field is mostly heading. The focus on specific climate, i.e. London, and a specific structure, i.e. aluminium, in addition to the lack of uncertainty analysis of the data through, for instance, Monte Carlo simulation can all be seen as limitations of this study and surely represent important and interesting areas for further research.

REFERENCES

ARDENTE, F., BECCALI, M., CELLURA, M. & MISTRETTA, M. 2011. Energy and environmental benefits in public buildings as a result of retrofit actions. *Renewable and Sustainable Energy Reviews,* 15**,** 460-470.

ASDRUBALI, F., BALDINELLI, G., D'ALESSANDRO, F. & SCRUCCA, F. 2015. Life cycle assessment of electricity production from renewable energies: Review and results harmonization. *Renewable and Sustainable Energy Reviews,* 42**,** 1113-1122.

BALA, A., RAUGEI, M., BENVENISTE, G., GAZULLA, C. & FULLANA-I-PALMER, P. 2010. Simplified tools for global warming potential evaluation: when 'good enough' is best. *The International Journal of Life Cycle Assessment,* 15**,** 489-498.

BLENGINI, G. A. & DI CARLO, T. 2010. The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings. *Energy and Buildings,* 42**,** 869-880.

BSI 2010. BS EN 15643-1:2010. Sustainability of construction works — Sustainability assessment of buildings. Part 1: General framework.

BSI 2011. PAS 2050:2011. Specification for the assessment of the life cycle greenhouse gas emissions of goods and services.

CABEZA, L. F., RINCÓN, L., VILARIÑO, V., PÉREZ, G. & CASTELL, A. 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.

CETINER, I. & OZKAN, E. 2005. An approach for the evaluation of energy and cost efficiency of glass facades. *Energy and Buildings,* 37.

CIBSE 2013. CIBSE TM 53: 2013 - Refurbishment of non-domestic buildings. Chartered Institution of Building Services Engineers - Great Britain.

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**,** 2653-2660.

DE BENEDETTI, B., TOSO, D., BALDO, G. L. & ROLLINO, S. 2010. EcoAudit: a Renewed Simplified Procedure to Facilitate the Environmentally Informed Material Choice Orienting the Further Life Cycle Analysis for Ecodesigners. *Materials transactions,* 51**,** 832-837.

DE GRACIA, A., NAVARRO, L., CASTELL, A., BOER, D. & CABEZA, L. F. 2013. Life cycle assessment of a ventilated facade with PCM in its air chamber. *Solar Energy*.

DIXIT, M. K., FERNANDEZ-SOLIS, J. L., LAVY, S. & CULP, C. H. 2012. Need for an embodied energy measurement protocol for buildings: A review paper. *Renewable & Sustainable Energy Reviews,* 16**,** 3730-3743.

FRISCHKNECHT, R., JUNGBLUTH, N. & AL., E. 2003. Implementation of Life Cycle Impact Assessment Methods. Final report ecoinvent 2000. Duebendorf, CH: Swiss Centre for LCI. .

GAKOVIC, B. 2000. Areas and types of glazing and other openings in the nondomestic building stock. *Environment and Planning B: Planning and Design,* 27**,** 667-694.
GRATIA, E. & DE HERDE, A. 2007. Are energy consumptions decreased with the addition of a double-skin? *Energy and Buildings,* 39.
HAMMOND, G. P. & JONES, C. I. 2008. Embodied energy and carbon in construction materials. *Proceedings of the ICE - Energy* [Online], 161. Available: http://www.icevirtuallibrary.com/content/article/10.1680/ener.2008.161.2.87.
IEA 2014. Technology Roadmap. Energy efficient building envelopes. Paris, France: International Energy Agency.
IES 2009. Building Energy and Environmental Modelling; Checklist for Choosing BEEM Software. ApacheSim.
IES 2014. MacroFlo Calculation Methods. Technical Manual.
JIN, Q. & OVEREND, M. 2013. A prototype whole-life value optimization tool for façade design. *Journal of Building Performance Simulation***,** 1-16.
KIM, G., SCHAEFER, L. A. & KIM, J. T. 2013. Development of a Double-Skin Facade for Sustainable Renovation of Old Residential Buildings. *Indoor and Built Environment,* 22**,** 180-190.
KOLOKOTRONI, M., ROBINSON-GAYLE, S., TANNO, S. & CRIPPS, A. 2004. Environmental impact analysis for typical office facades. *Building Research & Information,* 32**,** 2-16.
MALMQVIST, T., GLAUMANN, M., SCARPELLINI, S., ZABALZA, I., ARANDA, A., LLERA, E. & DIAZ, S. 2011. Life cycle assessment in buildings: The ENSLIC simplified method and guidelines. *Energy,* 36.
MONCASTER, A. M. & SONG, J. Y. 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**,** 26-36.
MONCASTER, A. M. & SYMONS, K. E. 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.
PAULIUK, S., SJÖSTRAND, K. & MÜLLER, D. B. 2013. Transforming the Norwegian dwelling stock to reach the 2 degrees Celsius climate target. *Journal of Industrial Ecology,* 17**,** 542-554.
REAP, J., ROMAN, F., DUNCAN, S. & BRAS, B. 2008. A survey of unresolved problems in life cycle assessment. *The International Journal of Life Cycle Assessment,* 13**,** 374-388.
SHAHRESTANI, M., YAO, R. & COOK, G. K. 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**,** 41-64.
SHAMERI, M. A., ALGHOUL, M. A., SOPIAN, K., ZAIN, M. F. M. & ELAYEB, O. 2011. Perspectives of double skin facade systems in buildings and energy saving. *Renewable & Sustainable Energy Reviews,* 15**,** 1468-1475.
STEADMAN, P., BRUHNS, H. R., HOLTIER, S., GAKOVIC, B., RICKABY, P. A. & BROWN, F. E. 2000. A classification of built forms. *Environment and Planning B: Planning and Design,* 27**,** 73-91.
STEVENSON, F. 2013. Reducing energy demand through retrofitting buildings. *Building Research & Information,* 41**,** 605-608.
TURCONI, R., BOLDRIN, A. & ASTRUP, T. 2013. Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations. *Renewable and Sustainable Energy Reviews,* 28**,** 555-565.
WADEL, G., ALONSO, P., ZAMORA, J.-L. & GARRIDO, P. 2013. Simplified LCA in skin design: The FB720 case. *International Journal of Sustainable Building Technology and Urban Development,* 4**,** 68-81.
WEIDEMA, B. P., THRANE, M., CHRISTENSEN, P., SCHMIDT, J. & LØKKE, S. 2008. Carbon Footprint: A Catalyst for Life Cycle Assessment? *Journal of Industrial Ecology,* 12**,** 3-6.
ZABALZA BRIBIÁN, I., ARANDA USÓN, A. & SCARPELLINI, S. 2009. Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification. *Building and Environment,* 44**,** 2510-2520.