Environmental and economic implications of building envelope design

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ABSTRACT: There is a wealth literature on operational energy consumption of buildings and how building skins contribute to that. Little is known about the life-cycle environmental impacts of building skins and it is not clear if the operational energy savings that are achieved by improvement strategies in building skin (such as more insulation, external shading devices, PV systems) would indeed result in lower environmental impacts from a life-cycle perspective. Even less clear is how economic and life-cycle environmental impacts of buildings would vary by the changes in architectural design parameters. In the present study, we quantify the variations in operational energy, environmental impacts and costs as a result of change in building skin design and construction parameters. We will examine building envelopes in low-rise office buildings from economic and environmental perspectives. For this purpose, 91 different design combinations of a building envelope are considered with different thermal resistance values of wall, wall-to-window ratios, window types, and frame materials. We then use Environmental Life Cycle Assessment (LCA) to study the variations of design combination with respect to global warming, acidification, eutrophication, and smog formation. Simultaneously, Life-Cycle Cost Analysis (LCCA) is applied to examine the cost changes in design combinations. Then, regression analysis is conducted to find the association between design combinations and changes in environmental impacts and cost fluctuations.

KEYWORDS: life-cycle assessment (LCA), life-cycle cost analysis (LCCA), building envelope

INTRODUCTION

Buildings are constructed with construction materials that entail high levels of embodied energy consumption over their life-cycle. Indeed, construction materials are responsible for about 6% of total primary energy consumed in the U.S. Since 1979, a focus of architectural practice and scholarship has been to find ways to reduce operational energy use of buildings which is the largest contributor to primary energy consumption. With the increased energy-efficiency of buildings, embodied energy is now regaining interest, especially that the improvement of design and construction for operational energy efficiency often leads to increased embodied energy. As an example, multiple-glazed windows have higher thermal resistance and therefore are more efficient in blockage of heat transfer and savings of operational energy, as compared with single-glazed windows, but higher amount of energy is used in manufacturing process of multiple glass panes. Limited number of studies explore the tradeoffs and synergies between building skin design, operational energy, embodied energy and other impacts on the environment.

1.0. LITERATURE REVIEW

Environmental Life Cycle Assessment (LCA) is the main methodology used for estimation of embodied energy and environmental impacts of products, processes, and buildings. The LCA methodology consists of four major phases of goal and scope definition, inventory modeling, impact assessment and interpretation of results. Process-based LCA, Economic Input-Output (EIO) LCA, and their hybrid LCA variants are major LCA techniques. In environmental process-based LCA, the environmental inputs (materials, energy) and outputs (waste, emissions) associated with each phase in a given product's life-cycle are identified, quantified and aggregated for the entire life cycle of the building (Heijungs & Suh 2002). The inputs and outputs are then converted into various categories of environmental impacts such as global warming, eutrophication, and acidification (Heijungs & Suh 2002). The EIO LCA method applies the US economy models and associates the monetary value of products to their environmental impacts (Hendrickson et al 2005). The hybrid methods take advantage of the methodological and data availability opportunities presented by each of the previous methods. Finally, a less known LCA method is ecologically-based LCA (Zhang 2010) that is based on an integrated ecological-economic model of the US economy and considers the role of eco-system services (biogeochemical cycles, disease regulations, etc.) too. Most LCA studies in the field of built environment tend to rely on process-based LCA.

The environmental impacts of building envelopes have been studied by several studies in the past. Kim (2011) conducted an LCA study on a transparent composite façade system (TCFS) and compared its environmental impacts with those of a glass curtain wall system. The research suggested that TCFS has a superior performance with regard to life cycle energy use and CO2 emissions (Kim 2011). Otteléa et al (2011) used LCA to compare the environmental impacts of non-vegetated brick walls, vegetated brick walls, and living wall systems in Netherlands. They showed that the living wall systems offered relatively lower environmental impacts, as compared with other systems. Stazi et al (2012) used an integrated energy-LCA analysis on a solar/Trombe wall and optimized energy and environmental life-cycle performance by considering parametric variations of wall materials, thickness, frame material, and glazing type. They concluded that the variation with concrete as wall material and aluminum as frame materials entails high environmental burdens.

2.0. METHODS

We used environmental life-cycle assessment (LCA) methodology to assess the life-cycle impacts on the environment. The functional unit for the LCA study was defined to be a building envelope of 1632 square foot (151.6 square meter) covering equal south and north façade areas of a low-rise office building. The system boundary for the LCA study includes the entire life-cycle of the building envelope from raw material extraction to manufacturing, construction, occupancy, and recovery/demolition.

We considered 91 design alternatives to a reference case based on variations in six design parameters. The design parameters of interest include insulation material type (Fiberglass batt, Fiberglass batt + expanded polyurethane), wall’s R-value (ranging from 11-21), window frame material type (fiberglass, wood vinyl, aluminum), glazing type (double-glazed, triple-glazed), and window-to-wall ratio (10-60%) on north and south facades. The operational energy consumption of each design alternative was estimated using eQuest 3.65 as energy simulation software and based on ASHRAE 90.1 assumptions to meet the energy code requirements. The operational energy performance results were then fed into the LCA software. Athena Impact Estimator (Athena IE) was used as the LCA software for life-cycle inventory modeling and impact assessment. Global warming potential (GWP) was the specific environmental impact category of interest.

The construction costs for the 91 design alternatives simulated in the paper were calculated using the 2015 Q3 RSMeans Online Construction Cost Data for new commercial buildings, localized for the Seattle (Washington state, USA) metropolitan area (RSMeans 2015). Wall components were classified following the CSI Master Format 2014. The required solid wall material quantities, and window surface area, were calculated based on the window to wall ratios and building dimensions specified for each of the design combinations studied. The resulting window surface area was then converted into individual 3’x5’ single hung window units. Cost estimates were computed based on the material, labor and installation equipment unit costs for the components used and the total quantities required of each. Labor costs are based on prevalent open-shop (non-union) productivity and man-hour cost for the various trades involved in the construction of the building envelope, while material costs are based on the procurement costs including associated delivery cost to the job site in the Seattle metropolitan area. Table 1 shows the detailed unit costs of materials used in design alternatives including the labor and installation costs.

Table 1. Unit costs of materials used in design alternatives

Material	Unit	Material	Labor	Equipment	Total	Bill Units	Mod	Cost ($)
1/2" Gypsum	sf	0.46	0.76	0	1.22	sf	1	1.22
8" Concrete	ea	1.82	2.65	0	4.47	Blocks	1	4.47
Air Barrier	sf	0.15	0.07	0	0.22	sf	1	0.22
Aluminum	lb	3.58	0.47	0.4	4.45	Tons	2000	8900
Aluminum	ea	369.51	70.14	0	439.65	lbs		0
Vinyl Clad	ea	490.84	36.57	0	527.41	lbs		0
Fiberglass	ea	490.84	32.57	0	523.41	lbs		0
Cold Rolled				0	0	Tons		0
Concrete Brick;	ea	0.62	2.08	0	2.7	sf	8	21.6
DG window;				0	0	sf	0.067	0
TG window; No				0	0	sf	0.08	0
Extruded	sf	0.55	0.36	0	0.91	sf (1")	1	0.91
Fiber Glass	sf	0.32	0.17	0	0.49	sf (1")	1	0.49
Glazing Panel				0	0	Tons	0	0
Joint	gal			0	0	Tons	0	0
Modified	sf	0.41	0.54	0.2	1.15	lbs	1.08	1.24
Mortar	cf	5.14		0	5.14	yd3	27	138.78
Nails					0	Tons	0	0
Paper Tape					0	Tons	0	0
Rebar, Rod,	lb	0.49	0.85		1.34	Tons	2000	2680
Split-faced	sf	3.99	3.91		7.9	Blocks	0.889	7.02

In the next phase of the research methodology, the effects of building skin design parameters on the changes in operational energy, global warming potential and cost were estimated. Multiple regression analysis was used as the statistical analysis technique with Stata SE as the tool for this purpose.

In this phase, first the data were explored visually in order to detect outliers and influential observations. Outliers are observations in a sample that deviate “markedly” from the rest of the observations in the sample (Grubbs, 1969); their presence in a model can skew the results of analysis. Influential observations are those observations having such extreme impact on the results that their inclusion in the model jeopardizes generalization of the results (Ting, 2004). The scatterplot matrix of the variables in the regression model was visually examined for outliers. These observations were excluded from the analysis.

Then, a bivariate regression model was run to test the bivariate relations between variables. Since the dependent variables in the model (i.e., energy use, global warming potential, and cost) are simultaneously affected by several design variables, multiple regression analysis was used to measure the effects on dependent variables. We then empirically examined the multiple regression model for other outliers/influential cases. Two statistical measures were applied for this purpose, including DfFit and studentized residuals. The model was re-run using the remaining cases in the model. In the next step, this model was examined for violation of other regression assumptions including non-linearity, non-normality, multicollinearity, heteroscedasticity, and misspecification. Non-linearity occurs when the relationship between independent and dependent variables is not linear. Non-normality refers to non-normal distribution of residuals. Multicollinearity occurs when the independent variables in the model exhibit near-perfect correlation with each other. Heteroscedasticity refers to the lack of equal variance of the residuals for independent variables (Miles & Shevlin, 2001) and is closely associated with non-normality. Misspecification happens primarily as a result of failing to include a major variable in the model, or including an irrelevant variable. Figure 1 illustrates the multiple regression methodology.

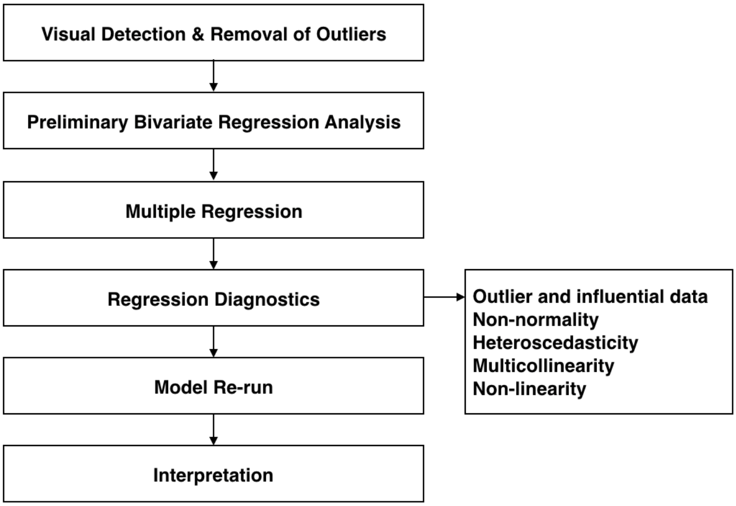

Figure 1. Regression analysis methodology

3.0. RESULTS

The regression analysis results for operational energy use, global warming potential and cost are shown in Tables 2, 3, and 4, respectively. The tables also report standardized beta coefficients for the regression results which help compare the effects of independent variables.

As shown in Table 2, the association between south WWR and operational energy use is negative; that is, increase in south WWR reduces energy use. More specifically, each unit increase in south WWR decreases energy use by -1.003. On the other hand, increase in north WWR increases operational energy use. The results also suggest that the effects of all design variables on operational energy use are statistically significant (p-value<0.05). R-value seems to be an exception which demonstrates a p-value of 0.08. This could be explained by high correlation between R-value and other variables in the model. The effects of all variables on operational energy use are negative, except for north WWR and changes in frame material which represent a positive effect. The adjusted R-squared of 0.6151 suggest that more than 61% of variations in operational energy use can be explained by five variables in the model.

Table 3 reports the multiple regression results for global warming potential. The results show that increase in north WWR and south WWR, and using high-performance windows reduce the global warming potential. This occurs mainly because the increase in WWR would lead to lesser use of insulation in the building envelope. Most insulation materials are energy-intensive with high global warming potential. The effects of the three variables are significant statistically. However, the effects of R-value and frame material on global warming potential are not significant in the sample studied by this research. The adjusted R-squared of 0.2106 suggest that about 21% of variations in global warming potential of the case-study building can be explained by the five variables in the model. This figure is not high enough and implies that there are other major variables affecting global warming potential that have not been included in the model.

Table 4 reports the results of multiple regression on cost variable. The variable with greatest effect on cost is window type as high-performance windows are often associated with increased construction cost. It is important to note that the cost factor studied here is not life cycle cost of the project, rather initial construction cost. The higher costs of high-performance windows can be balanced by the energy-related cost savings over the life span of the building. The results also show that south and north WWR both represent negative effects on cost; that is, increase in south and north WWR reduces the cost of the project. This could be explained by significant amount of construction materials (e.g. insulation, brick veneer, gypsum board, etc.) that would not be needed by increase in WWR. Among the design variables in the model, wall R-value and frame materials also have a positive effect on cost; i.e., they lead to increase in costs. The adjusted R-squared of 0.860 suggest that more than 86% of variations in construction cost can be explained by WWR, R-value (i.e., insulation), windows and frames.

Table 2. Multiple Regression Model with Operational Energy as Dependent Variable

Number of Observations = 91	F(5,85) = 29.77	R-squared = 0.6365
Root MSE=2.7108	Prob > F = 0.0000	Adjusted R-squared = 0.6151

Variable	Slope Coefficients	Standard Error	T	P>t	Beta
South WWR	-1.003	0.240	-4.17	0.000	-0.274
North WWR	1.158	0.240	4.82	0.000	0.316
Window type	-8.152	0.844	-9.65	0.000	-0.634
R-value	-0.242	0.089	-2.70	0.008	-0.177
Frame mater.	1.614	0.496	3.25	0.002	0.213
Constant	198.744	2.286	86.91	0.000	.

Table 3. Multiple Regression Model with Global Warming Potential as Dependent Variable

Number of Observations = 91	F(5,85) = 5.80	R-squared = 0.2544
Root MSE=32.768	Prob > F = 0.0001	Adjusted R-squared = 0.2106

Variable	Slope Coefficients	Standard Error	T	P>t	Beta
South WWR	-9.151	2.906	-3.15	0.002	-0.296
North WWR	-8.418	2.906	-2.90	0.005	-0.272
Window type	-29.515	10.210	-2.89	0.005	-0.272
R-value	-2.057	1.085	-1.90	0.061	-0.178
Frame mater.	8.415	6.006	1.40	0.165	0.132
Constant	1994.227	27.643	72.14	0.000	.

Table 4. Multiple Regression Model with Cost as Dependent Variable

Number of Observations = 91	F(5,85) = 112.12	R-squared = 0.868
Root MSE=6.015	Prob > F = 0.0000	Adjusted R-squared = 0.860

Variable	Slope Coefficients	Standard Error	T	P>t	Beta
South WWR	-2.682	0.533	-5.03	0.000	-0.198
North WWR	-2.682	0.533	-5.03	0.000	-0.198
Window type	31.077	1.874	16.58	0.000	0.656
R-value	2.874	0.199	14.42	0.000	0.570
Frame mater.	9.935	1.102	9.01	0.000	0.356
Constant	-45.318	5.074	-8.93	0.000	.

Comparison of standardized Beta coefficients revealed that improving glazing material (triple-glazed versus double-glazed) has the highest effect on operational energy use, followed by WWR on north and south facades. Results also show that the association between operational energy use and south WWR is an inverse association while its association with north WWR is positive. The results also showed the increase in north WWR, south WWR and wall's R-value would lead to lower life-cycle global warming potential. Using aluminum frames also can increase the GWP potential, although the results seem to be statistically insignificant.

CONCLUSIONS

We empirically studied the effects of 5 design variables including south WWR, north WWR, R-value, window type, and frame materials on operational energy use, global warming potential, and cost in a low-rise office building using process-based LCA and regress analysis. The use of multiple regression analysis allows to capture and isolate the effects of multiple design parameters on the changes in operational energy use, GWP and cost. The results revealed that the independent design variables including north WWR, south WWR, glazing type, R-value and frame material type have a statistically significant effect on all dependent variables; i.e., operational energy use, GWP and cost. The effect of insulation material type on dependent variables, however, was not significant statistically, mainly because of its high correlation with the R-value. The results also reflect the complex relationship between operational energy and global warming as one variable could increase one while decreasing the other.

While the research result can be useful to the research and professional communities, caution should be taken in interpreting the results and generalizing them to other contexts. The results reflect the climatic and geographical context of Seattle in Washington State. Other locations have different climates and manufacturing and transportation practices which would affect the operational energy use and life-cycle environmental impacts of buildings. Also,

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