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OPTIMIZING BUILDING DESIGN WITH RESPECT TO LIFE-CYCLE ENVIRONMENTAL IMPACTS

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ABSTRACT

Since buildings have a predominant impact on the global climate change and other environmental issues, it has become necessary to consider environmental performance in building design. An optimization approach is presented in this paper to minimize life-cycle environmental impacts of buildings. Parameters included in the model are usually determined at the conceptual design phase and have a critical influence on environmental performance. Life-cycle environmental impacts are evaluated in terms of expanded cumulative exergy consumption. It is the sum of exergy consumption due to resource inputs and abatement exergy required to recover the negative impacts due to waste emissions. The optimal solution is found using structured genetic algorithms. A case study is presented.

INTRODUCTION

Climate change is one of the major global environmental challenges facing the whole world today. It has been established by the International Panel of Climate Change (IPCC) that man-made greenhouse gas emissions are at the root of the climate problem. The enhanced greenhouse effect tends to alter atmospheric and oceanic temperatures, weather patterns, and the entire hydrological cycle. Besides the climate change, there are also some other environmental challenges such as acidification, stratospheric ozone depletion, urban air pollution, loss of biological diversity and so on. Both climate change and other environmental problems result to a large extent from emissions arising from human activities, in particular, the burning of fossil fuel (IPCC 2001).

Buildings are energy gluttons and have a large impact on the global climate change and other energy-related environmental issues. It is reported by the U.S. Department of Energy that buildings account for 36% of total primary energy consumption and 67% of electricity consumption (DOE 2002). As a direct result, buildings account for nearly 35 percent of CO_2 emissions, 48 percent of SO_2, and 20 percent of NO_x (DOE 2002). In response to the buildings' major impact on the environment, it is important to explore ways for a better building design that considers environmental performance.

Many studies have been made in order to optimize building design for energy efficiency. They used the operating energy consumption or life-cycle cost as the single performance criterion to establish optimization models (Miller 1992; Al-Homoud 1997; Wetter 2001; Coley and Schukat 2002). Because the optimal solutions corresponding to life-cycle cost and operating energy consumption are usually different, the cost is treated as a constraint in the study of Peippo et al. (1999) to investigate the impacts of economical constraint on energy-efficient measures. Despite the above efforts, two major limitations undermine their application in practical building design. They are discussed below.

Inappropriate environmental performance criterion. Although operating energy is considered explicitly or implicitly in previous studies, the embodied energy and the corresponding environmental impacts are neglected. This may be due to the following three reasons: the unavailability or inconsistency of data for environmental impact of building materials and components; few life-cycle environmental impacts simulation programs are available; both designers and clients have little interests in reducing embodied environmental impacts because they are not directly related to building costs. However, the optimal solution derived from the minimization of operating energy consumption may not be the desired one if the timescale is extended to cover the whole life-cycle of buildings. As indicated by Yohanis and Norton (2002), increasing operating energy efficiency makes embodied energy considerations more important. Furthermore, energy consumption is no longer a complete criterion to evaluate environmental performance because many environmental impacts associated with material production are not energy-related. This makes it necessary to incorporate the holistic impact categories covering natural resource depletion, global warming potential, and so on, into the objective function.

Improper variable determination. Variables vary with studies in many ways such as quantities and types. The inappropriateness of variables can be seen in two ways. In the first case, the variable type is not properly defined. It is not difficult to observe that many parameters such as window types can only take discrete values. Probably because of the difficulty in dealing with discrete variables in numerical optimization methods, developers often resort to related continuous variables to solve the problem. For example, the window type is represented by its thermal resistance value (Miller 1992). In the second case, some variables in the model are not directly design-oriented, but are intermediate results from other direct design options. Sometimes this gap cannot be easily handled. For example, given optimal value for time lag (Al-Homoud 1997), designers may find it difficult to map the optimal results to a corresponding design solution.

In recognition of the above limitations of former studies, a new optimization model is proposed in this paper. Since this model relies on exergy and related concepts, these are introduced in the second section. Then, the optimization model and the algorithm employed to solve the formulated problem are described. Finally, a case study is presented.

EXERGETIC LIFE-CYCLE ASSESSMENT

Life-Cycle Assessment (LCA) is an analytical tool that can help in understanding and evaluating the resource consumption and waste emissions associated with products, packaging, processes and activities across all stages of their life cycle from materials acquisition to final disposition (ISO 1997). The life-cycle of buildings is shown in Figure 1. The dashed line denotes the scope considered in this optimization study.

As indicated by Barnthouse et al. (1998), global, long-lived impact categories usually have characteristics that can be dealt with by LCA with acceptable theoretical accuracy, but the aggregated LCA indicators for local and transient impact categories have little practical meanings. Therefore, impact categories considered in this optimization study include resource consumption and those waste emissions that have global/continental and long-lasting impacts on the environment, namely, CO_2, CH_4, N_2O, SO_x, and NO_x.

It is difficult, however, to characterize natural resource depletion and to integrate various impact categories with different units and magnitudes in the context of life-cycle optimization. Available approaches for characterizing resource depletion in the context of LCA are reviewed by Finnveden (1994). Although methods based on reserves and reserve-to-use ratios have been used in many studies, it is highly difficult to aggregate the depletion indices for different resources. Normalization cannot completely address this difficulty because different normalization coefficients may lead to conflicting conclusions. Weighting integration is a technique that is often employed to compare alternatives once their impact profiles are defined. Reference points are required to normalize impact categories with quite different magnitudes. However, without widely accepted reference points in current literatures, it is problematic to apply weighting integration in design optimization because the optimal results vary with different reference choices. The use of exergy can overcome these problems of resource characterization and weigthing integration with former methods.

According to Moran and Sciubba (1992), exergy is "the maximum theoretical work that can be extracted from a combined system consisting of the system under study and the environment as the system passes from a given state to equilibrium with the environment---that is, passes to the dead state at which the combined system possesses energy but no exergy". Unlike energy, exergy is always destroyed because of the irreversible nature of the process. Exergy is an extensive property whose value is fixed by the state of the system once the environment has been specified. Therefore, the evaluation of exergy depends on both the state of a system under study and the conditions of the reference environment. Most applications of exergy analysis in the published literatures concentrate on thermal system design (Moran 1982) and chemical and metallurgical process analysis (Szargut et al. 1988). The exergy can also be incorporated into LCA to address the issues of natural resource depletion characterization and valuation.

Cumulative exergy consumption (CExC) proposed by Szargut et al. (1988) expresses the sum of the exergy of all natural resources consumed in all the steps of a production process. Unlike cumulative energy consumption, it takes into account the exergy of the nonenergetic raw materials extracted from the environment. Therefore, cumulative exergy consumption can be used to measure natural resource depletion.

Exergy is not only a measure of resource consumption; it is also a measure of waste emissions. Because exergy can evaluate the degree of disequilibrium between a substance and its environment, some rational and meaningful relationships can be established between the environmental impact potentials and the exergy of waste emissions (Ayres et al. 1998). Abatement exergy is employed in this study to evaluate the required exergy to remove or isolate the emissions from the environment. Although the value of abatement exergy for a given waste emission is technology-dependent, it is possible to determine an average abatement exergy for each emission, for instance, 5.86, 57, and 16 MJ/kg for CO_2, SO_x, and NO_x, respectively (Dewulf et al. 2001).

Thus, by extending the cumulative exergy consumption to include abatement exergy, all the resource inputs and waste outputs can be unified together. This expanded cumulative exergy consumption can consider both resource inputs and waste emissions to the environment. It is particularly suitable for life cycle optimization with respect to environmental performance. The main advantages can be summarized as:

- It can combine resource depletion and waste emissions together, and therefore, the life cycle environmental impacts can be condensed into one single objective function.
- It can combine energetic resources and nonenergetic materials together to characterize the resource depletion.
- Only one criterion is employed to avoid weights or other qualitative judgement in the evaluation of environmental impacts.

A demanding task in applying exergetic life-cycle assessment is to collect consistent and reliable data for analysis. Because no database is available that can directly provide cumulative exergy consumption and environmental impacts covering typical building materials and constructions, ATHENA (Trusty and Meil 2002), a life-cycle assessment tool specially developed for buildings, is employed here to extract the natural resource consumption and waste emissions. These data can be used to derive cumulative exergy consumption and abatement exergy. ATHENA is selected because of its prominent advantages in the following aspects.

- The ATHENA database is continuously updated for the North American conditions.
- It can offer values of environmental impacts for each life-cycle stage with details. These values are essential to derive cumulative exergy consumption and other environmental impacts.
- It covers typical materials or assemblies for building structure and envelope.
- The components of an assembly defined in ATHENA are more construction-oriented because they have considered overlap, waste and other miscellaneous ancillary materials. This particular advantage makes it convenient to locate corresponding cost found in databook such as R.S.Means (2002).

OPTIMIZATION MODEL AND ALGORITHM

Optimization Model

Variables are those parameters that define a building design and are passed to a building simulation program. For example, window type is a variable in the system. It can be set to several window alternatives or to a constant if the window type is fixed by the designer. There are two types of variables: discrete and continuous. Some variables such as window type can only be of discrete type while some variables (e.g., orientation) can be either continuous or discrete.

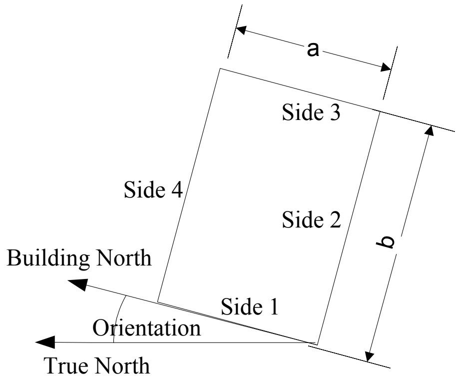

Figure 2 Definition of orientation and aspect ratio

In this research, buildings are limited to a rectangular shape with known total floor area. Figure 2 is used to illustrate the definition of some variables. The variables are:

- Building Orientation (orientation).
- Aspect Ratio (aspectRatio) defined as *a/b*, where *a* and *b* are shown in Figure 2.
- Window Type (winType).
- Window area ratio for each building façade *i* ($winRatio_i$).
- Wall Type (wallType).
- Each Layer of wall (wallLayer). The total number and the arrangement of layers are dependent on wall type.
- Roof Type (roofType).
- Each Layer of Roof (roofLayer). The total number and the arrangement of layers are dependent on roof type.

Because it is essential to explore the trade-off between economical performance and environmental performance, Life-Cycle Cost (LCC) and Life-Cycle

Environmental Impact (LCEI) are coupled together using weighted scalarization method in this research. Assuming **X** is the variable vector, the integrated objective function *F(X)* can be expressed as:

$$F(\mathbf{X}) = w_1 * LCEI(\mathbf{X}) + w_2 * LCC(\mathbf{X}) \qquad (1)$$

where w_1 and w_2 are predefined weights for life-cycle environmental impact and life-cycle cost respectively.

LCEI is the life-cycle environmental impact using exergy as an indicator criterion. The general expression to calculate LCEI is:

$$LCEI(\mathbf{X}) = EE(\mathbf{X}) + OE(\mathbf{X}) \qquad (2)$$

where, EE=Embodied exergy, that is, the expanded cumulative exergy consumption due to building construction;

OE=Operating exergy, that is, the expanded cumulative exergy consumption due to building operation.

The general expression to calculate LCC is:

$$LCC(\mathbf{X}) = IC(\mathbf{X}) + OC(\mathbf{X}) \qquad (3)$$

where, IC=Initial construction cost;

OC=Operating cost, including both demand and energy consumption costs.

The ASHRAE toolkit for building load calculations (Pedersen et al. 2000) is coupled with the optimization module to estimate the annual energy consumption and peak electric demand.

Structured Genetic Algorithm

The selection of an optimization algorithm depends on the particularities of a problem domain. The previous formulated problem has the following characteristics:

- Hard combinatorial problem. If the following variables and corresponding number of alternatives (the number in parenthesis) are considered: orientation(10), aspectRatio(10), winType(3), wallType(3), roofType(3), $winRatio_i(10)$, each $wallLayer_j(5)$, each $roofLayer_j(5)$, with *i*=4 and *j*=5, then there are about $2.6*10^{10}$ possible solutions to explore.
- Both continuous and discrete variables may exist in the same optimization problem.
- The shape of criteria space is unknown.

Genetic Algorithms (GA) are good at exploring large search space because of its implicit parallel computation mechanism. The binary string representation can deal with both continuous and discrete variable. Compared with conventional numerical methods, genetic algorithms are able to locate global optimum without trapping into local extreme point. All these advantages determine that GA is an appropriate candidate to solve the above formulated problem. However, since the layer arrangement is dependent on the high-level wall/roof type that they are associated with, a simple GA implementation will cause a large amount of infeasible solutions if the hierarchical relationship between wall/roof type and wall/roof layers is not specially distinguished. Structured GA can address the above problem by maintaining the hierarchical relationship in the GA representation.

The structured GA proposed by Dasgupta and McGregor (1994) represents the chromosome as hierarchical genomic structures. Whether low-level genes are dominant or recessive depends on high-level genes. The novelty of the structured GA lies in its redundant genetic materials and a gene activation mechanism.

CASE STUDY

Problem Formulation

A single-story office building located in Montreal, Canada is employed in this paper as a case study. The building has a total floor area of 1000 m^2 with 40-year life expectancy. Only the energy consumed in the cooling season (June, July and August) is considered. Rooftop units with a COP (Coefficient of Performance) of 3.0 are assumed to be used. Emission factors due to electricity consumption are $6.47*10^{-3}$ kg/MJ (for CO_2), $2.48*10^{-7}$ kg/MJ (CH_4), $6.75*10^{-8}$ kg/MJ (N_2O), $2.08*10^{-5}$ kg/MJ (SO_x), $6.63*10^{-6}$ kg/MJ (NO_x). They are calculated based on the electricity mix in Montreal and emission factors with each primary fuel. Cumulative exergy consumption is 4.17 MJ for each MJ of electricity (Szargut et al. 1988). The general inflation rate, discount rate, and energy escalation rate are 3%, 5% and 1%, respectively. The structure of electricity rate is: $11.97 per KW of billing demand, $0.0372 per KWh for the first 210000 KWh, $0.0242 per KWh for the remaining electricity consumption.

The variables are given in Table 1. Low-e double glazing with 12.7 mm air space is the window type selected for this building. There are two possible wall types: masonry cavity wall and steel-frame wall type. The first wall type is composed of the following layers in sequence from outside to inside: cladding, air space, rigid insulation, structure, vapor barrier, and finishing. The second wall type is composed of cladding, air space, air barrier, sheathing, steel-stud with insulation, vapor barrier, and finishing. Six rigid insulation alternatives are offered for the first wall type: expanded polystyrene and extruded polystyrene with three thickness values (25.4mm, 50.8mm, and 76.2mm) for each. Six insulation alternatives are offered for the second wall type: fiberglass batts with three thickness (88.9mm, 152.4mm and 228.6mm) and rockwool batts with three thickness values (88.9mm, 152.4mm and 254mm). Only one roof type is considered at this stage but several types can be integrated later. It is a compact conventional roof system composed of ballast, roofing membrane, insulation, structure, and finishing. Rigid insulation alternatives are the same as those in the first wall type. However, cost for the same material may vary with construction positions. For example, costs for 25.4mm expanded polystyrene on wall and on roof are 6.67 and 4.84 $\$/m^2$, respectively (R.S. Means 2002).

Table 1 Variable instantiation

Potential Variable Name		Actual Type	Range or Value
orientation		Continuous	[0, 90]
aspectRatio		Continuous	[0.1, 1.0]
winType		Constant	Double Low-e
winRatio1		Continuous	[0.2, 0.8]
winRatio2		Continuous	[0.2, 0.8]
winRatio3		Continuous	[0.2, 0.8]
winRatio4		Continuous	[0.2, 0.8]
wallType		Discrete	(1, 2)
roofType		Constant	Compact conventional roof
Layer of wall Type1	cladding	Constant	Brick veneer
	other	Constant	20mm air space
	insulation	Discrete	(1, 2, 3, 4, 5, 6)
	structure	Constant	100mm concrete block back-up
	membrane	Constant	6 mil polyethylene
	finishing	Constant	12.7mm Gypsum
Layer of wall Type2	cladding	Constant	Brick veneer
	other	Constant	20mm air space
	membrane	Constant	Asphalt sheathing paper
	sheathing	Constant	12.7mm oriented strand board
	insulation (stud)	Discrete	(1, 2, 3, 4, 5, 6)
	membrane	Constant	6 mil polyethylene
	finishing	Constant	12.7mm Gypsum
Layer of roof Type	other	Constant	ballast
	membrane	Constant	4-ply Built-up
	insulation	Discrete	(1, 2, 3, 4, 5, 6)
	structure	Constant	OWSJ and steel decking
	finishing	Constant	12.7mm Gypsum

For the structured GA implementation, the following parameters are specified as: crossover probability p_c=0.9, mutation probability p_m=0.05, maximum number of generations=100, population size=20. Tournament selection and elitist strategy are used in this GA implementation.

Results and Discussion

Four weighting sets are used in this study. The two extreme cases (case 1 and case 4) are actually single performance criterion optimization with the life-cycle environmental impact and life-cycle cost as the objective function respectively. The minimum function value obtained from the two extreme weighting sets are used to normalize the life-cycle environmental impact and life-cycle cost in weighting case 2 and 3. The program for each weighting set is run three times. The optimal values of variables obtained from the best run of each weighting set are presented in Table 2. It can be seen from this table that:

- The optimal aspect ratio is about 0.55 when the optimization criterion is the life-cycle environmental impact, and 0.98 for the life-cycle cost.
- For all weights considered in the study, the optimum design requires the maximum thickness of thermal insulation of the roof.
- Masonry cavity wall is better than framed wall type when environmental performance is the only criterion. However, framed wall is recommended when the life-cycle cost is considered in the overall criterion.
- For masonry cavity wall, 50.8 mm expanded polystyrene is the optimal insulation for environmental performance. This indicates that the thermal resistance of insulation material in masonry cavity wall is not as critical as that in the roof due to their differences in orientation and surface area.
- The minimum allowed window area is preferred for both environmental and economical performance.

The building performance corresponding to each optimal solution is also shown at the bottom of Table 2. Besides life-cycle environmental impact and life-cycle cost, two other common performance criteria, life-cycle energy and annual operating energy, are also presented to study the influence of weights on different performance.

The evolution of the best solution ever found for life-cycle environmental impact and life-cycle cost (case 1 and case 4) is shown in Figure 3 and Figure 4, respectively. The process evolves rapidly during the first 30 generations, and then slowly at later generations. This demonstrates that genetic algorithms can perform better in locating the optimal region than in local search. It can be observed that the optimization is effective to improve building performance. Compared with the function value of the initial best solution, the final optimal value decresed by 15% and 7% for life-cycle environmental impact and life-cycle cost, respectively.

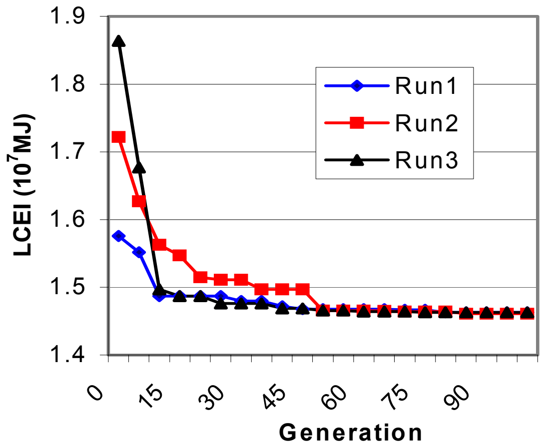

Figure 3 Life-cycle environmental impact convergence

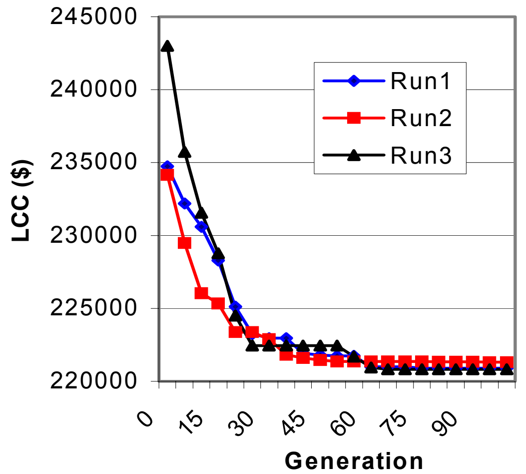

Figure 4 Life-cycle cost convergence

CONCLUSION

Optimization is an effective approach for better building design. Since variables are design-oriented, the optimal layer alternatives can be used directly. The variables can be customized easily by designers according to design situations. Particularly, the structured formulation between wall/roof types and layer components make it possible to simultaneously optimize variables in different hierarchical levels.

Exergy is a useful concept to be employed in life-cycle environmental optimization problems. It can overcome the difficulty brought by integrating impacts with varied magnitudes and units. With expanded cumulative exergy consumption, the optimization problem can be simplified by incorporating all impact categories into one objective function.

Because the economical performance and environmental performance cannot take optimal values at the same time, a multi-criteria optimization model is highly useful for decision-making in an environment-friendly building design. A disadvantage of the weighted scalarization technique is that only one optimal value is obtained for each weighting set. Different weighting sets need to be tested to explore different optimal solutions.

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REFERENCES

Al-Homoud, M. 1997. Optimum thermal design of office buildings, *International Journal of Energy Research*, Vol. 21, pp. 941-957.

Ayres, R.U., Ayres, L.W., and Martinas, K. 1998. Exergy, waste accounting, and life-cycle analysis, *Energy*, Vol.23, No.5, pp. 355-363.

Barnthouse, L., Fava, J., Humphreys, K., Hunt, R., Laibson, L., Noesen, S., Norris, G., Owens, J., Todd, J., Vigon, B., Weitz, K., and Young, J. 1998. Life-Cycle Impact Assessment: The State-of-the-Art, 2nd edition, SETAC Press, Pensacola, FL.

Coley, D.A. and Schukat, S. 2002. Low-energy Design: Combining Computer-based Optimization and Human Judgement, *Building and Environment*, Vol.37, pp. 1241-1247.

Dasgupta, D. and McGregor, D.R. 1993. sGA : A Structured Genetic Algorithm, Technical Report. IKBS-11-93, Dept. of Computer Science, University of Strathclyde, UK.

DOE. 2002. BTS Core Databook. U.S. Department of Energy.

Dewulf, J., Langenhove, H. V., and Dirckx, J. 2001. Exergy analysis in the assessment of the sustainability of waste gas treatment systems, *Science of the Total Environment*, Vol. 273, pp. 41-52.

Finnveden, G. 1994. Methods for describing and characterizing resource depletion in the context of life-cycle assessment, Technical Report, Swedish Environmental Research Institute, Stockholm, Sweden.

IPCC, Intergovernmental Panel on Climate Change, 2001. Climate change 2001: synthesis report, Cambridge University Press.

ISO. 1997. ISO 14040: 1997 Environmental management—Life cycle assessment—Principles and framework, International Organization for Standardization.

Miller, B.E. 1992. Optimizing Building Design Variables, *M.S. Thesis*, Department of Mechanical Engineering, Colorado State University, Fort Collins, CO.

Moran, M.J. 1982. Availability analysis: a guide to efficient energy use, Prentice-Hall, Englewood Cliffs, N.J.

Moran, M.J., and Sciubba, E. 1994. Exergy analysis: principles and practice, *Journal of Engineering for Gas Turbines and Power*, Vol. 116, April, pp. 285-290.

Peippo,K., Lund,P.D., and Vartiainen, E. 1999. Multivariate optimization of design trade-offs for solar low energy buildings, *Energy and Building*, Vol. 29, pp. 189-205.

Pedersen, C.O., Liesen, R.J., Strand, R.K., Fisher, D.E., Dong, L., and Ellis, P.G. 2000. A Toolkit for Building Load Calculations, ASHRAE, Atlanta, GA.

RS Means. 2002. Building Construction Cost, Kingston, MA.

Szargut, J. Morris, D.R., and Steward, F.R. 1988. Exergy Analysis of Thermal, Chemical, and Metallurgical Process, Hemisphere Publishing, New York.

Trusty, W.B. and Meil, J.K. 2002. Introducing ATHENA V2.0: an LCA based decision support tool for assessing the environmental impact of the built environemnt, Proceedings of eSim 2002, IBPSA-Canada, Montreal.

Wetter, M. 2001. GenOpt—A generic optimzation program, Proceedings of the Seventh International IBPSA Conference, Rio de Janeiro, Brazil, pp. 601-608.

Yohanis, Y.G. and Norton, B. 2002. Life-cycle operational and embodied energy for a generic single-story office building in the UK, *Energy*, Vol. 27, pp. 77-92.

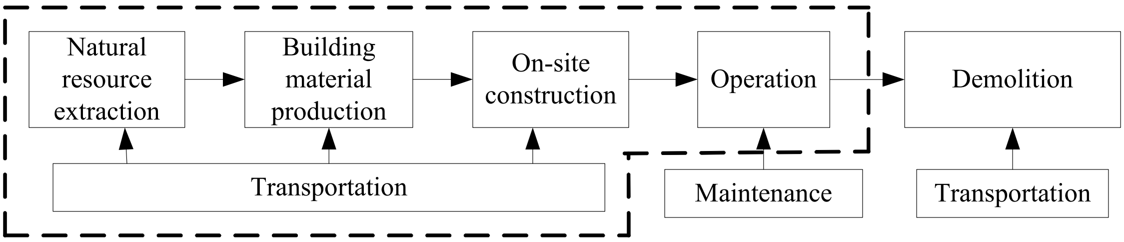

Figure 1 Building life-cycle process

Table 2 Optimal solutions for different weights w_1 and w_2

Items		Weights			
		W_1=1.0, W_2=0.0	**W_1=0.7, W_2=0.3**	**W_1=0.3, W_2=0.7**	**W_1=0.0, W_2=1.0**
Variables	orientation	3.5	0	0	82
	aspectRatio	0.55	0.77	0.93	0.98
	winRatio1	0.2	0.2	0.2	0.2
	winRatio2	0.2	0.2	0.22	0.2
	winRatio3	0.2	0.2	0.2	0.2
	winRatio4	0.2	0.2	0.2	0.2
	wallType	1	2	2	2
	Insulation of wallType1	2	-	-	-
	Insulation of wallType2	-	3	3	6
	Insulation of roof	6	6	6	6
Performance	LCEI (MJ)	$1.461*10^7$	$1.484*10^7$	$1.496*10^7$	$1.502*10^7$
	LCC ($)	255235	221323	221070	220891
	Life-cycle energy (MJ)	$4.378*10^6$	$4.442*10^6$	$4.468*10^6$	$4.482*10^6$
	Annual cooling energy (KWh)	20752	21045	21254	21344