Development of a life cycle cost optimization tool for buildings

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ABSTRACT

Life cycle cost of building involves two components, initial cost and recurring cost. Recurring cost involves energy and maintenance expenditure during the service life of the building. Designers today want to design buildings with minimum overall ownership cost. At the design time there is flexibility in choosing values for different design variables. Since there are many design variables and there can be many likely values for each variable, several combinations are possible. The effect of these variables on the initial cost and recurring cost is very complicated. This paper describes a tool—Life Cycle Cost Optimization for Buildings (LCCOB)—which has been developed to optimize material properties and building envelope using Life-Cycle Cost (LCC) as the optimization criterion. Inputs to the tool consist of building information including the design variables, cost information and objective function. The tool calculates the initial cost of the building, estimates energy requirements per year using EnergyPlus and optimizes LCC using GenOpt. It runs many simulations with varying values of design variables and minimizes the LCC. Case studies performed by using this tool demonstrate the significance of LCC optimization.

INDEX TERMS

Life cycle cost; Optimization; Building design; Energy

INTRODUCTION

The design process of a building involves fulfilling user requirements, comfort, aesthetics, cost and energy conservation. The designer is expected to design in such a way that the life cycle cost of the building is minimum. There are a large number of design variables that can be varied while designing a building. These variables have impact on initial as well as recurring cost. A major component of the recurring costs is energy consumption. Computer simulation can be used to evaluate the energy performance of buildings for different values and combinations of these design variables. There can be many designs possible because of the large number of parameters and their combinations. It becomes difficult for the designer to understand the influence of different design parameters on the LCC of building. The tedious process of changing values, running the simulation, interpreting new results and changing the values in a suitable direction in order to achieve optimal results is very complex. Optimization is a tool to replace manual variation of different design variables. It not only saves the designer from running many simulations but also finds the minimum possible value of life cycle cost.

For optimization of building energy performance or minimizing the costs involved in any building, a number of techniques can be applied. Numerical as well as analytical approaches have been adopted in the past to achieve minimal thermal loads (Jurovics, 1978) and to optimize insulation thickness to minimize costs (Bagatin *et al*., 1984). Direct search algorithms have been applied to minimize the annual energy consumption (Al-Homoud, 1997) and genetic algorithms to optimize building heating systems (Dickinson and Bradshaw, 1995).

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An optimization method has been proposed which is based on minimization of the life cycle cost constrained by performance requirements (Nielsen, 2002).

This paper describes a tool, Life Cycle Cost Optimization for Buildings (LCCOB), which has been developed to optimize material properties and building envelope using Life Cycle Cost (LCC) as the optimization criterion. Inputs to the tool consist of building information including the design variables, cost information and objective function. The tool calculates the initial cost of the building, uses EnergyPlus for estimating the energy requirements and GenOpt for optimization of LCC. It runs many simulations with varying values of design variables and minimizes the LCC. The methodology implemented in the tool is tested on many case studies.

Life Cycle Cost

Life cycle costing is now being widely used for evaluating various design proposals. LCC of a building is calculated based on investment cost, recurring cost, replacement cost and scrap value. One of the methods (Nielsen 2002) gives the LCC as

$$\mathrm{lcc} = \left(\sum \mathrm{Ic}.(1+r)^{-n.\mathrm{SL}}\right) + (\mathrm{Mc}+\mathrm{Ec}).\frac{1-(1+r)^{-N}}{r} - Sv.(1+r)^{-N} \quad (1)$$

with life cycle cost lcc, yearly energy cost Ec, investment cost Ic, yearly maintenance cost Mc, scrap value Sv, service life SL, real interest rate r and calculation period N.

What is EnergyPlus?[1]

Energy Plus is a building energy simulation program for modelling building heating, cooling, lighting, ventilating, and other energy flows. Based on user description of a building from the perspective of the building's physical make up, associated mechanical system etc., EnergyPlus calculates the heating and cooling loads necessary to maintain thermal comfort set point conditions throughout a simulation.

What is GenOpt? (Wetter, 2001)

GenOpt is a generic optimization program. It minimizes an objective function with respect to multiple parameters. The objective function is evaluated by a simulation program that is iteratively called by GenOpt.

WORKING OF LCCOB

The user provides building information and the LCC optimization parameters using the IDF editor provided with EnergyPlus or by directly creating a file using text editor. The tool LCCOB has two components 'Configuration utility' and 'CostEvaluator'. Configuration utility reads a .idf file, takes building data along with LCC optimization requirements and creates various files, including the template file, to be used by GenOpt. It then invokes GenOpt which uses EnergyPlus and the CostEvaluator repeatedly to optimize the LCC. The CostEvaluator calculates the initial cost of building for each iteration and procures the energy data from EnergyPlus output. It calculates various energy costs based on the inputs given by the user in the .idf file. LCC is calculated by this module based on a user-defined function. The input data dictionary Energy+.idd has been modified so that the IDF editor can be used for input of optimization parameters and additional information required by GenOpt. This dictionary is an ASCII (text) file containing a list of all possible EnergyPlus objects and specification of data each object requires. The IDF editor uses this file for creating appropriate objects in the editor.

[1]U.S. Department of Energy, Washington DC, USA. URL: http://www.eren.doe.gov/buildings/energy-tools/energyplus.

A group 'Life cycle cost optimization' has been added to the dictionary file. The classes and their functionality in this group are given below:

- *'Variable in materials' (there are different classes for different kind of materials)*
  This class is used to create an object, which denotes a variable for a material property. This variable is given a unique name that is used as a variable parameter by GenOpt. The user specifies the initial, minimum, maximum and step size for the variable.
- *'Cost of material' and 'cost of construction'*
  These objects are used to give the cost of material and construction. If cost is a function of some varying property of building material it can be given as a formula.
- *'Variable in coordinates' and 'surfaces with variable coordinates'*
  When surfaces are varied as an optimization parameter, the coordinates defining the surface have to be defined as variables. Such variable coordinates are defined in 'variable in coordinates' object and the variables are put in the corresponding coordinates of 'surfaces with variable coordinates' object.
- *'What variables from Eplus output'*
  EnergyPlus gives the output in an .eso file. Values of report-variables including energy consumption are given in this file. The file has a data dictionary, which lists the variable IDs followed by a variable name. Below the dictionary are the variable IDs followed by their values. To get the variable IDs, the user must first simulate the .idf file without the CostEvaluator component. The user then inputs these IDs in the object 'what variables from Eplus output'. A field for defining the cost function for these variables is also provided. The user can access the value of the variable by using the name of the variable in the calculations.
- *'Calculate various energies' and 'calculate various costs'*
  User fills data in this object for reported and optimization variables. It should be noted that there can be only one optimization variable in a problem. *Bcost* is an inbuilt variable available from the costing module. This gives the total building cost, excluding the costs of equipment, furniture, etc. The user can use this variable for life cycle costing.

Interaction of LCCOB with EnergyPlus and GenOpt

Interaction of the two components of LCCOB with EnergyPlus and GenOpt is shown in Figure 1. Configuration utility takes the input from the .idf file and generates four files viz. template file, initialization file, command file and configuration file. All these four files form the input for GenOpt. Configuration utility then invokes GenOpt. GenOpt updates the variables in the template file, creates a .idf file and invokes EnergyPlus with this .idf file as input. After the completion of EnergyPlus simulation, control is transferred to CostEvaluator. The standard output file (.eso) from EnergyPlus and .idf file updated by GenOpt form the input for CostEvaluator. CostEvaluator calculates the initial cost of building, energy costs, LCC of building and any other variable as defined in the .idf file and write this data into the .lcc file. The .lcc file is input to GenOpt for reading the value of LCC. Based on the value of LCC, GenOpt updates the variables, creates a new .idf file and invokes EnergyPlus. This loop continues till LCC is optimized. The loop is shown by dotted lines in Figure 1.

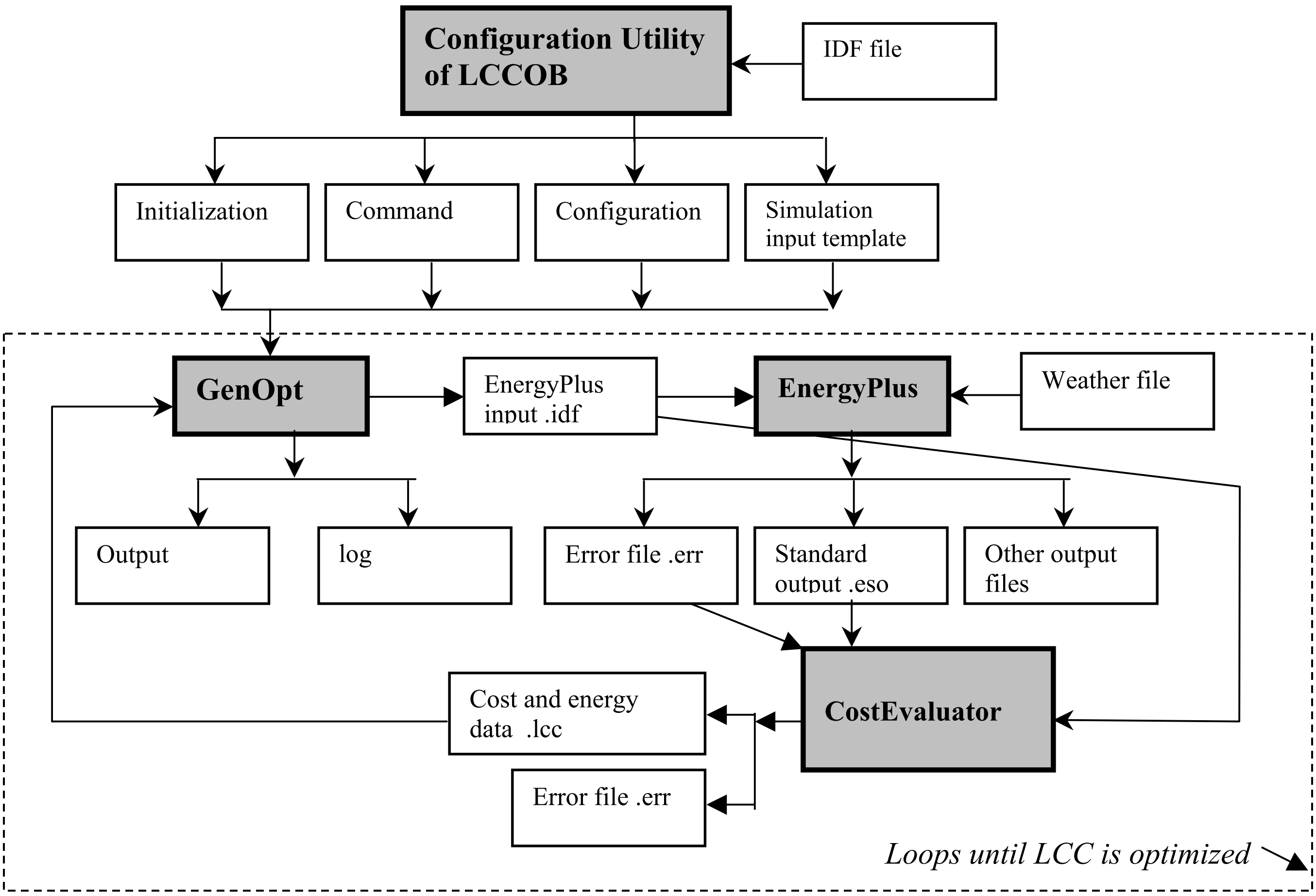

Figure 1 Interaction between two components of LCCOB, EnergyPlus and GenOpt.

STATUS OF LCCOB

LCCOB is still under development. The beta version for testing and feedback is available. Interested beta testers can get a limited time evaluation license by sending mail to vishal@iiit.net.

CASE STUDIES

Two case studies were conducted. Each consisting of two runs to compare optimization of LCC with optimization of energy. The first run took optimization of LCC as the objective function for a room with fixed geometry but alterable material properties: thickness of insulation and wall. The second run considered energy as the objective function for the same room.

Building Description

The building geometry was described in EnergyPlus using the IDF editor. It consisted of a single room 6 m × 6 m × 3 m. A window was placed on the south wall. All the walls were exposed to the outside environment. Variables were assigned to material properties: wall thickness and insulation thickness, to evaluate the effect of change of these properties on the costs and energy usage.

Outer Wall Construction

In case II the outer walls consisted of four layers, viz. the outer stucco, common brick (variable thickness), wall insulation (variable thickness) and the inner plaster. In case I, the wall insulation was not included. The properties of the materials used for the outer wall are given in Table 1. Cost function gives the cost of materials. When a property of the material is variable, cost becomes a function of that property, as shown in the table.

Roof Construction
In case I the roof was made of four layers of materials, viz. slag, felt, dense insulation and dense concrete from outside to inside. In case II the roof insulation was removed. The description of the materials is given in Table 1.

Table 1 Properties and cost function of materials used in construction

Material property	Stucco	Common brick	Plaster	Slag	Felt	Dense insulation	Dense concrete
Thickness (m)	0.025	Variable	0.019	0.012	0.009	Variable	0.050
Conductivity (W/m K)	0.691	0.726	0.726	1.435	0.190	0.04	1.729
Density (kg/m^3)	1858	1922	1601	881	1121	160	2242
Specific heat (J/Kg K)	836	836	836	1673	1673	836	836
Cost function (Rs./m^2)	60	1200× thickness	60	100	50	15 000× thickness	150

Window Construction
The window was a single pane with fixed geometry of 2.4 m × 1 m and was placed on the south wall.

Design Options
The layout and the orientation of the building were fixed. The position and size of the window were also fixed. The parameters that were varied in optimization were the thickness of outer walls and insulation. The thickness of the wall varied from 100 mm. to 1000 mm. in steps of 50 mm and insulation varied from 9 to 150 mm in steps of 1 mm. The life of the building was assumed to be 40 years for LCC.

Optimization Results
Case I
In the first run, the building design was optimized for total energy consumption over its life and in the second run for its life cycle cost. In these simulations there was no insulation on walls. Roof insulation and wall thickness were made variable. Table 2 gives the results of the two optimization runs.

Table 2 Results of LCC optimization and energy optimization for Case I

	LCC Optimization	Energy Optimization
Energy consumption (GJ).	10.095	8.364
LCC (Rs.)	7 48 742	9 94 695
Thickness of outer walls (m)	0.11	0.99
Thickness of roof insulation (m)	0.07	0.15

Case II
In this case roof insulation was not considered. Insulation thicknesses of all the four walls varied independently of each other. Wall thickness was also a variable but all the walls had the same thickness. The comparison of LCC versus energy optimization is summarized in

Table 3. For LCC optimization the results recommend the building to have maximum insulation on the east and west walls, the wall thickness being 0.556 m. The value suggested for wall thickness is not practical considering the loss of utilizable area. If carpet area is also used in estimating the cost of building the results will be more appropriate. This example is taken only to demonstrate the working of the tool.

Table 3 Results of LCC optimization and energy optimization for Case II

	LCC Optimization	Energy Optimization
Energy Consumption (GJ)	21.637	20.863
LCC (Rs.)	1 300 959	1 325 674
Thickness of outer walls (m)	0.556	1
Thickness of insulation (m)	0.009 (North and South) 0.029 (East and West)	0.009 (same for all walls)

CONCLUSION

The work presented in this paper evaluates the importance of LCC optimization in designing a building. The goal of this building optimization tool is to achieve minimum life cycle cost without compromising the occupant's comfort.

As the LCC reaches a minimum value, the energy costs for the building are not generally minimum. The same holds good for the reverse case. This work intends to explore the benefits of both LCC and energy optimizations and infer the results for a more logical design approach. Test simulations were run for a design problem. The results show that when the LCC is optimized for a building, the excess energy consumed is about 20% more than when the energy is optimized. However, in the reverse case, the excess LCC is of the order of 33%.

These results may vary with more realistic design problems. However, they give a fair insight into the optimization approach to be adopted at the design stage of any building project.

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