STEPS TOWARD DESIGNING A POSITIVE ENERGY HOUSE: LESSONS LEARNT

Amir Rezaei Bazkiaei¹ and Raghuram Sunnam²

¹High Performance Design Specialist, MKK Consulting Engineers Inc., Greenwood Village, CO; Email: arezaei@mkkeng.com
²Building Performance Analyst, Baumann Consulting, Washington D.C.; Email: rsunnam@baumann-us.com

ABSTRACT
This paper outlines the steps and measures taken in designing a positive energy residential building in a cold climate. The design team was given a fixed set of occupant schedules and zone characteristics to design with. Several energy modeling tools were employed early on in the design process to identify the best passive strategies that meet the building loads. The envelope thermal properties were optimized by utilizing GenOpt tool. In the next step, natural ventilation controls were optimized based on the ambient air temperatures and wind-driven ventilation potential. After reducing the building loads to an optimal value and leveraging the internal gains at different times of the year, the energy needs of the building were met by solar PV panels and wind turbines. Initial envelope optimization resulted in approximately 80% reduction of the total energy use intensity (EUI) to 34 kWh/m², which meets the Architecture 2030 challenge requirements. The key strategies to meet this low EUI were high efficiency ground source heat pump (GSHP), air heat recovery, PV and wind production. This paper discusses the lessons learnt and the applicability of the tools to create a smooth workflow for the design of a positive energy house.

INTRODUCTION
Researchers in the USA and European union have been studying Net zero energy buildings to (1) reduce energy consumption; (2) reduce greenhouse gas emissions; (3) make the operation of buildings more economical (EISA, 2007) (EPBD, 2010). Moving further from the objective of net zero energy consumption, this study presents a study of various steps involved in the design of a net positive Energy house. This study was carried out as a part of a design competition and was not based on an actual design project. The participants were given a fixed set of inputs (including all floor plans, internal gains, schedules, room set points, etc.) and were asked to design a net-positive energy house in for cold climatic conditions in Chambéry, France. It was assumed that the entire attic level would be used to house the mechanical equipment as the area requirement calculations was not within the scope of the competition.

To achieve net-positive energy performance, design process was broken into four stages:
1. Identify extreme weather indicators through weather analytics.
2. Reduce the internal heat gains and solar heat gains to take advantage of passive strategies.
3. Optimize the active mechanical systems to reduce the energy consumption.
4. Assess the applicability of electricity generation sources to meet the remainder of the energy usage.

CLIMATE ANALYSIS
ClimateConsultant 3.0 tool was used for weather analysis as it is capable of reading EPW (EnergyPlus Weather) format that was provided (Milne et al., 2007). On average, the outside air temperatures from May to September for the location were close to the comfort criteria defined by ASHRAE Guideline 55 (ASHRAE, 2007). To achieve near-zero energy performance for the building, the focus was to eliminate the energy requirements for cooling and to minimize heating demand. It was noticed that the wind speeds varied between 2 to 4 m/s in the north-south orientation. This observation was important for a cross-ventilation strategy through Natural Ventilation.

The key lessons from the climate analysis were:
- 11.3% of the total hours in the year are comfortable (989 hours) based on the ASHARE 55 comfort criteria.
- 52.4% of the total hours required heating (4591 hours).
- 28.2% of the total hours benefitted from internal heat gains. (2473 hours).
9.1% of the total hours benefitted from passive solar direct gain high mass (800 hours).
8.9% of the total hours require sun shading for the windows (777 hours).
2% of the total hours require dehumidification only (175 hours).
1.4% of the total hours require cooling, might need dehumidification. (121 hours).

This analysis effectively laid the foundation for the rest of design decisions. It was decided that reliance on internal gains and optimizing insulation could reduce the heating loads while relying on natural ventilation could lower the cooling loads and push significant number of hours to the comfort zone.

Figure 1: ClimateConsultant Psychrometric chart analysis for 8760 hours of outside air temp.

ENVELOPE OPTIMIZATION

Optimization of the envelope insulation is a multi-objective problem (Caldas et al., 2003) and this study particularly focused on the effectiveness of the tool – GenOpt for such an optimization. GenOpt optimization tool was used in conjunction with Energyplus simulation engine for this purpose.

The goal was to automate the selection process by choosing a wide range of envelope properties and let the optimization tool find the most optimal combination of properties that favor the building energy loads. This was done in two steps with different range of insulation values for the opaque wall construction. Impact of different surface orientations was accounted for by allowing different properties on four orientations of the building. The list of variables and their respective ranges are as follows:

- Wall R-values, varying from R1 to R100 with 0.1 m²K/W increment
- Roof R-values, varying from R1 to R100 with 0.1 m²K/W increment
- Slab on grade R-values, varying from R1 to R100 with 0.1 m²K/W increment
- Window U-value, varying from 0.5 to 3 with 0.1 W/m²K increments
- Window SHGC, varying from 0.1 to 0.9 with 0.1 increments

A sample snapshot of the GenOpt run window is depicted in Figure 2. The y-axis shows the values of variables and EnergyPlus outputs (R-values, heating and cooling load and total facility load) for each iteration and x-axis shows the iteration number. The snapshot shows the evolution of optimization algorithm at the approximate simulation number of 1500. It can be seen that the algorithm has started with an initial range of variables at the beginning and is proceeding to the optimal solution. The values obtained from the optimization runs were carefully used as initial best guesses that optimize the building energy loads and were subsequently compared to lower and higher insulation values in a parametric study to obtain the least building loads. Figure 3 shows the variation of the total building energy use intensity with increasing opaque envelope R-value in the presence of optimal glazing system thermal properties. The results in Figure 3 show that with the fixed windows’ thermal and glazing properties, the return on investing on R-values above 30-40 m²K/W rapidly diminishes.

Figure 2: GenOpt simulation console snapshot

To evaluate the impact of thermal properties of windows, a comparison was made for the models with R-values from 20-40 m²K/W. A SHGC=0.6 instead of the obtained optimal value of 0.3 was used in separate runs for the R-value range. In another comparative run, window U-factors were changed to 1 W/m²K in place of the optimal 0.6 W/m²K obtained from the optimization while the SHGC was kept at 0.3 (Figure 4).

© 2016 ASHRAE (www.ashrae.org). For personal use only. Additional reproduction, distribution, or transmission in either print or digital form is not permitted without ASHRAE’s prior written permission.
Given that the climate condition is heating dominated, increasing the solar gains through the envelope seemed a reasonable option. It was observed that the balance between the heating load reduction and cooling load increase still favors the utilization of SHGC=0.3, U-factor= 0.6 W/m²K with the opaque material R-value of 40 m²K/W. Therefore, these values were chosen to be used as the envelope thermal properties for the rest of simulations.

NATURAL VENTILATION

The natural ventilation (NV) was modeled by constructing an Airflow network model in EnergyPlus connecting the windows and interior doors to create a pathway for cross-flow ventilation. The key parameters for successful modulation of windows with this EnergyPlus NV model are the opening factor of assigned surfaces to the Airflow network model, lower and upper temperature difference for modulation and the zone temperature threshold above which NV is engaged (Figure 5).

An optimization run was set up in GenOpt tool with the variables defined in the appendix A. The goal of optimization was to find the values of natural ventilation setpoint and control variables for modulation of windows that provide spaces with maximum possible natural cooling in summer. The objective function was set to minimize the indoor operative temperature of the zones in the hottest day in June to minimize the runtime of the simulation.

The optimal natural ventilation set points were 24 ℃ for Apr-Sept, except for June and July where the set points were 22.5 ℃. The resulting modulation control options were: Maximum opening factor= 1, lower temperature differential for modulation= 4.3 ℃, and upper temperature differential for modulation= 16.7 ℃.
The optimized parameters were used to compare the results (Figure 6a) to a non-optimal variation of the natural ventilation controls (Figure 6b) for the living room. The graphs depict the window modulation factors during the 8760 hours of the year in relation to the outdoor temperatures. The window modulation in Fig.6b with optimized variables demonstrates a considerably different pattern than the non-optimal Fig.6a. With the optimal variables, it appears that the windows modulate during more hours to take advantage of NV and a smoother pattern of window opening can be observed with varying outdoor temperatures which would not have been achievable with the non-optimal settings (Fig. 6a).

MECHANICAL SYSTEMS
Although cooling loads were minimal for the building, it was required to have a cooling coil to meet the cooling load during peak summer hours. VAV reheat boxes were used as terminal distribution equipment at the zones. A plate heat exchanger with 75% sensible energy recovery efficiency was included in the design to take advantage of the heating season exhaust air energy recovery.

A vertical ground loop connected to a water-to-water heat pump was used as the primary source of energy feeding the heating and cooling coils of the air-side system. Connection to district heating and cooling was added as a backup for peak demand times during extreme summer and winter hours.

GENERATION
Rooftop PV panels and wind generation were chosen for the house to push the design to net-positive status. A conservative value of 12% PV production efficiency and 50% of roof area were assigned to PV generation. The prevailing North-South wind, with speeds as high as 4 m/s, was recognized as the second source of electricity generation.

ENERGY RESULTS
The design energy breakdown indicates that heating is the main HVAC consumer with the internal equipment/lighting to follow. This indicates that the internal gains were optimized to allow for heating and an energy use intensity, 34.4 kWh/m², was achievable before including generation capacity. Air-side heat recovery accounted for nearly half the heating season energy needs. The PV and wind generation capacities pushed the design over to net-positive.

<table>
<thead>
<tr>
<th>Source</th>
<th>KWH</th>
<th>KWH/M²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site</td>
<td>5811.9</td>
<td>34.4</td>
</tr>
<tr>
<td>Net Site</td>
<td>-12527.6</td>
<td>-74.2</td>
</tr>
</tbody>
</table>

Table 1 Total energy consumption

<table>
<thead>
<tr>
<th>Source</th>
<th>KWH</th>
<th>% TOTAL ELECTRICITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV</td>
<td>4074.1</td>
<td>71.4</td>
</tr>
<tr>
<td>Wind</td>
<td>14265.5</td>
<td>250.2</td>
</tr>
</tbody>
</table>

Table 2 Electricity generation from sources

Another way to look at the effectiveness of design is by assessing the energy flows in and out of the building on
an annual basis (Figure 10). This graph does not show the equipment electricity consumption for maintaining the indoor temperatures rather shows the amount of total energy flows via different sources (internal, external and sensible HVAC air energy). The timing of when the gains occur is also not fully characterized in this graph but the overall picture helps understand the energy balance. It can be observed that the gains and losses of the house are fairly balanced.

CONCLUSION

The emphasis in the study was on effectively using energy modeling tools to reach a positive-energy design. It is arguable whether the use of lengthy optimization techniques is always a standard practice in designing high performance buildings for real life projects. For example, it may not practically be possible to constantly generate the amounts of energy through solar or wind generation. The focus of the study is to assess a methodology to utilize the various energy simulation platforms to analyze the available data to assist with designing projects with high performance goals. Ensuring that such designs transcend into actual performance would further require multiple checks and balances at each project stage.

The following is a summary of the lessons learnt having approached the design by the steps outlined in the previous sections of this paper.

1. Relatively fast weather analytics were very powerful in determining the direction of design but care should be taken in interpreting the climate data analysis. The ClimateConsultant psychrometric graphs are based on conditional analysis of outdoor air temperature and moisture for the 8760 hours of the year. This means that the program looks at the indoor comfort range in heating and cooling then compares the number of hours that the outdoor conditions can directly satisfy or have the potential to satisfy with passive/active strategies. It is important to keep in mind that there are critical simplifying assumptions in proposing the suitable strategies that need to be carefully examined before strategies can be fixed. For example, the psychrometric chart does not consider the impact of radiant temperatures on comfort analysis or the fact that the availability of direct solar gain can be diminished by site location as well as the windows and shading object designs.

2. It was possible to evaluate the combined effect of a large number of design variables with the optimization tool. Take the NV study for example; fine-tuning the temperature thresholds to maximize the NV potential that best corresponded with the hourly climate data would have needed numerous parametric runs and forensic work on an hourly basis that would have required more time than setting up an appropriate optimization run. This study did not look at additional optimization variables such as HVAC controls/settings or scenarios with more competing design alternatives (e.g., adding skylights to reduce lighting but increasing heating/cooling needs) but it is foreseeable that such optimization techniques will be more advantageous when there are a growing number of design variables with competing energy consequences.

3. The GenOpt optimization run for envelope insulation was set up to simulate for select hot/cold days so that the optimization runtime could be minimized. Most of the optimization runs were able to generate results overnight.

4. The Airflownetwork model is best suited for a detailed analysis of air flow inside buildings via different sources such as cracks, buoyancy and wind forces. Various assumptions including the crack air flows and building pressure drop coefficients for this project were taken from EnergyPlus default values because these are hard values to obtain for an actual
Overall, the utilization of the optimization tools in conjunction with the energy modeling engines requires considerable knowledge of key variables reflective of the design needs and the workflow to reach the final results needs more fine-tuning. Whether similar optimization techniques will be viable options for larger scale project remains unknown given the time intensity of these simulations but it can be noted that simplifying assumptions such as block zoning, selective time periods and breaking the optimization runs into separate steps can help simplify these optimization runs. Given that net-zero to positive-energy designs are becoming more of a necessity to reach the climate action goal (Sartori et al., 2012), the need for workflows such as the one presented in this paper are inevitable. Such workflows with the available modeling packages need to be flexible enough to be applicable for different projects and would need further discussions on the granularity levels based on specific project needs.

APPENDIX A

GenOpt code for envelope optimization:

GenOpt command line for envelope study was used to search for the range of wall, roof, and slab on grade wall R-values as well as window U-values and SHGCs. The variables are defined for each face of the building.

```
Vary { Parameter{ // Wall1 R-Value Name = WR1; Min = 1; Ini = 2; Max = 100; Step = 0.1; } Parameter{ // Wall2 R-Value Name = WR2; Min = 1; Ini = 2; Max = 100; Step = 0.1; } Parameter{ // Wall3 R-Value Name = WR3; Min = 1; Ini = 2; Max = 100; Step = 0.1; } Parameter{ // Wall4 R-Value Name = WR4; Min = 1; Ini = 2; Max = 100; Step = 0.1; } Parameter{ // Roof R-Value Name = RoofR; Min = 1; Ini = 2; Max = 100; Step = 0.1; } Parameter{ // Slab R-Value Name = SlabR; Min = 1; Ini = 2; Max = 30; Step = 0.1; } Parameter{ // Window1 SHGC Name = SHGC1; Min = 0.1; Ini = 0.5; Max = 0.9; Step = 0.1; } Parameter{ // Window2 SHGC Name = SHGC2; Min = 0.1; Ini = 0.5; Max = 0.9; Step = 0.1; } Parameter{ // Window3 SHGC Name = SHGC3; Min = 0.1; Ini = 0.5; Max = 0.9; Step = 0.1; } Parameter{ // Window4 SHGC Name = SHGC4; Min = 0.1; Ini = 0.5; Max = 0.9; Step = 0.1; }
```

```
OptimizationSettings{ MaxIte = 10000; MaxEqualResults = 100; WriteStepNumber = false; UnitsOfExecution = 5; }
Algorithm{ Main = GPSPSOCCHJ; NeighborhoodTopology = vonNeumann; NeighborhoodSize = 50; NumberOfParticle = 50; NumberOfGeneration = 50; Seed = 20; CognitiveAcceleration = 2.8; SocialAcceleration = 1.3; MaxVelocityGainContinuous = 0.5; MaxVelocityDiscrete = 4; ConstrictionGain = 0.5; MeshSizeDivider = 2; InitialMeshSizeExponent = 0; MeshSizeExponentIncrement = 1; NumberOfStepReduction = 4; }
```

GenOpt configuration file script:

```
// Error messages of the simulation program.
SimulationError { ErrorMessage = "** Fatal **"
ErrorMessage = "** EnergyPlus Terminated--Error(s)
Detected**"; }
// Number format for writing the simulation input files.IO{ NumberFormat = Double; }
/* Specifying how to start the simulation program.
In "Command", only those words in %xx% are
replaced (possibly with empty Strings).
*/ SimulationStart { // The command line below calls RunEPlus.bat.
WriteInputFileExtension = false; }
```

© 2016 ASHRAE (www.ashrae.org). For personal use only. Additional reproduction, distribution, or transmission in either print or digital form is not permitted without ASHRAE’s prior written permission.
- GenOpt initiation file for envelope study that reads the location of the idf and template files to be used with GenOpt:

```plaintext
*/Simulation {  Files {    Template {      File1 = model_v5_Template.idf;    }    Input {      File1 = model_v5.idf;    }    Log {      File1 = model_v5.err;    }    Output {      File1 = model_v5.eso;    }  }

Configuration {      File1 = "../..\cfg\EnergyPlus-8.cfg";    }  }

CallParameter { // optional section    // The weather file without extension    Suffix = FRA_Lyon.074810_IWEC;  }

ObjectiveFunctionLocation  {      Name1 = Facility_J;      Function1 = "add( %Q_Heat%, %Q_Cool%)";      Name2 = Q_Cool;      Delimiter2 = "685,";      FirstCharacterAt2 = 1;      Name3 = Q_Heat;      Delimiter3 = "654,";      FirstCharacterAt3 = 1;  } // end of section Simulation

Optimization {  Files {    Command {      File1 = command.txt;    }   } } // end of configuration file
```

- GenOpt code for natural ventilation study:

```plaintext
- GenOpt command file for natural ventilation optimization:

```plaintext
*/Vary{  Parameter{    Name = NVSet;    Min = 10;    Ini = 20;    Max = 27;    Step = 0.1; } Parameter{    Name = LoDelC;    Min = 0;    Ini = 5;    Max = 6;    Step = 0.1; } Parameter{    Name = UpDelC;    Min = 6.1;    Ini = 8;    Max = 20;    Step = 0.1; } Parameter{    Name = OFact;    Min = 0.1;    Ini = 0.5;    Max = 1;    Step = 0.05; } OptimizationSettings{    MaxIte = 5000;    MaxEqualResults = 100;    WriteStepNumber = false;    UnitsOfExecution = 5; } Algorithm{    Main = GPSPSOCCHJ;    NeighborhoodTopology = vonNeumann;    NumberOfGeneration = 50;    NumberOfParticle = 100;    Seed = 50;    CognitiveAcceleration = 2.8;    SocialAcceleration = 1.3;    MaxVelocityGainContinuous = 0.5;    MaxVelocityDiscrete = 4;    ConstrictionGain = 0.5;    MeshSizeDivider = 2;    InitialMeshSizeExponent = 0;    MeshSizeExponentIncrement = 1;    NumberOfStepReduction = 4; } // end of section Simulation
```

- GenOpt initiation file commands for natural ventilation study:

```plaintext
*/Simulation {  Files {    Template {      File1 = NV_Optimization_Template.idf;    }    Input {      File1 = NV_Optimization.idf;    }    Log {      File1 = NV_Optimization.err;    }    Output {      File1 = NV_Optimization.eso;    }  }

Configuration {      File1 = "../..\cfg\EnergyPlus-8.cfg";    }  }

CallParameter { // optional section    // The weather file without extension    Suffix = LeBourgetDuLac;  }

ObjectiveFunctionLocation  {      Name1 = Living_Temp;      Delimiter1 = "151,";      FirstCharacterAt1 = 1;  } // end of section Simulation
```

Airflow Network components

- AirflowNetwork:SimulationControl,
  - Natural Ventilation,
  - MultizoneWithoutDistribution,

INPUT,  
- Wind Pressure Coefficient Type
  - Every 30 Degrees,
- AirflowNetwork Wind Pressure Coefficient Array Name
  - ExternalNode,
  - Height Selection for Local Wind Pressure Calculation
  - LOWRISE,
  - Building Type
  - 500,
- Maximum Number of Iterations
  - {dimensionless}
  - ZeroNodePressures,
  - Initialization Type
  - 1.0E-05,
- Relative Airflow Convergence Tolerance {dimensionless}
  - 1.0E-06,
- Absolute Airflow Convergence Tolerance {kg/s}
  - -0.5,
- Convergence Acceleration Limit {dimensionless}
  - 0.0,
- Azimuth Angle of Long Axis of Building {deg}
  - 1.0,
- Ratio of Building Width Along Short Axis to Width Along Long Axis

AirflowNetwork:MultiZone:Component:SimpleOpening,
  - DrOpen,
  - Name
```

© 2016 ASHRAE (www.ashrae.org). For personal use only. Additional reproduction, distribution, or transmission in either print or digital form is not permitted without ASHRAE’s prior written permission.
0.667, !- Air Mass Flow Exponent When Opening is Closed {dimensionless}
0.0001, !- Minimum Density Difference for Two-Way Flow {kg/m3}
0.5; !- Discharge Coefficient {dimensionless}

AirflowNetwork:MultiZone:Component:SimpleOpening,
WiOpen, !- Name
0.001, !- Air Mass Flow Coefficient When Opening is Closed {kg/s-m}
0.667, !- Air Mass Flow Exponent When Opening is Closed {dimensionless}
0.0001, !- Minimum Density Difference for Two-Way Flow {kg/m3}
0.6; !- Discharge Coefficient {dimensionless}

Idf template variables marked for NV optimization:
Schedule:Compact,
WindowVentSched2, !- Name
Any Number, !- Schedule Type Limits Name
Through: 3/31, !- Field 1
For: AllDays, !- Field 2
Until: 24:00, !- Field 3
25.5, !- Field 4
Through: 9/30, !- Field 5
For: AllDays, !- Field 6
Until: 24:00, !- Field 7
%NVSet%, !- Field 8
Through: 12/31, !- Field 9
For: AllDays, !- Field 10
Until: 24:00, !- Field 11
25.5; !- Field 12

AirflowNetwork:MultiZone:Zone,
00_Living, !- Zone Name
Temperature, !- Ventilation Control Mode
WindowVentSched2, !- Ventilation Control Zone Temperature Setpoint Schedule Name
0.5, !- Minimum Venting Open Factor {dimensionless}
%LoDelC%, !- Indoor and Outdoor Temperature Difference Lower Limit For Maximum Venting Open Factor {deltaC}

AirflowNetwork:MultiZone:Surface,
W1_4, !- Surface Name
WiOpen, !- Leakage Component Name
NFacade, !- External Node Name
%OFact%; !- Window/Door Opening Factor, or Crack Factor {dimensionless}

REFERENCES