The Use of Genetic Algorithms for a Net-Zero Energy Solar Home Design Optimisation Tool

Rémi Charron[1] and Andreas Athienitis[2]

[1]Photovoltaic and Hybrid System Program, CANMET Energy Technology Centre, Varennes, Canada
[2]Building, Civil and Environmental Engineering Department, Concordia University, Montreal, Canada

ABSTRACT: The application of computerised optimisation techniques to the design of low and net-zero energy buildings would provide building designers with a powerful design tool. This paper presents such a tool that is being developed that links TRNSYS energy simulation with an optimisation program based on genetic algorithms. This early design stage optimisation tool optimises 17 parameters including building width to length ratio, heating system type, solar thermal collector type and size, window sizes by orientation, and more, to find multiple design configurations that achieve a set energy consumption target.

Keywords: optimisation, genetic algorithms, low energy, solar home

1. INTRODUCTION

Homes that utilise solar thermal and solar photovoltaic (PV) technologies to generate as much energy as their yearly load are referred to as net-Zero Energy Solar Homes (ZESH). In the last 25 years, there have been many one-of-a-kind demonstration projects and international initiatives that have promoted the development of low and net-zero energy homes [1]. More recently, as countries are starting to implement measures to reduce green house gas emissions to address global warming, interest in ZESH has increased. Traditional design tools were not developed to facilitate the design and optimisation of these high performance houses, and thus a new design optimisation tool, introduced in this paper, is being developed to help address this issue.

Designing a ZESH involves the coupling of many different systems to achieve an energy efficient design, which also generates on-site energy using renewable energy technologies to satisfy its yearly energy needs. The design involves the use of various types of systems, which can vary depending on the specific design objectives, the project location, the knowledge of the designer, etc., all of which lead to many different configurations of ZESH. This can be observed by examining the various net-zero and low energy building demonstration projects from around the world [1]. These projects depended on trial-and-error optimisation using dynamic energy simulation tools, coupled with the knowledge of the designers. Simulations are normally used in a scenario-by-scenario basis, with the designer generating one solution and subsequently having a computer evaluate it. This can be a slow and tedious process and typically only a few scenarios are evaluated from a large range of possible choices [2]. Although a reduction in the energy use of residential buildings can be achieved by relatively simple individual measures, very high levels of performance require the coherent application of measures, which together optimise the performance of the complete building system. This multi-component optimisation problem can lead designers to feel ill equipped to tackle such a task. The application of computerised optimisation techniques to the design of low and net-zero energy buildings would provide architects and engineers with a powerful design tool [3].

In recent years, Genetic Algorithms (GA) have been used to optimise different building systems including optimising solar collector and storage tank size [4], a low energy community hall including shape of perimeter, roof pitch, constructional details of envelope, window types, locations and shading, and building orientation [3], window size and orientation [2], conceptual designs of office buildings [5], HVAC sizing, control, room thermal mass [6], and more. The use of GA in optimising buildings and other engineering problems is emerging as this global search technique is adequate for searching “noisy” solution spaces with many local and global minima, and has proved to have high efficacy in solving complex problems for which conventional “hill-climbing” derivative-based algorithms are likely to be trapped in local solutions [2]. Another advantage of using GA is that it provides a population of optimum designs. In [3] the GA found countless possible design solutions for a low energy community hall that used less energy than comparable buildings in the UK. What is even more useful is that the optimum designs can be very different, giving a great deal of choice to the designer and/or building owner. For example, two of the more optimal designs that evolved in [3] had very similar energy use, but were very different. One used high levels of insulation to reduce losses with minimal window area, while the other focused more on maximising passive solar utilisation by having more windows and more thermal mass.

This paper presents a new early stage ZESH design optimisation tool that is being developed. The paper will describe the GA algorithm used as well as the building energy simulation model developed in TRNSYS. An analysis is presented to determine whether a one- or two-zone building model would be most appropriate for the tool.

2. MODEL DESCRIPTION

2.1 Tool overview

In Figure 1, a flow chart is presented that shows the basic principles of the design optimisation tool being developed. First, a random population of individual designs will be generated with random configurations. The GA program will then call TRNSYS to determine the energy use and comfort of each design in the population. Once all the designs in the population have been evaluated, the GA program will calculate the fitness of each individual. In this case the fitness will be the inverse of the combined monthly costs of purchased energy plus the amortised cost of the energy efficient and renewable energy upgrades as discussed further in section 2.3. Once the termination criterion of the GA is met (based on convergence, maximum amount of generations, etc.) the program will be stopped, and the results analysed. If the termination criterion is not met, then the GA program will create a new generation of designs by using selection, recombination, and mutation and the program is iterated until the termination criterion is met.

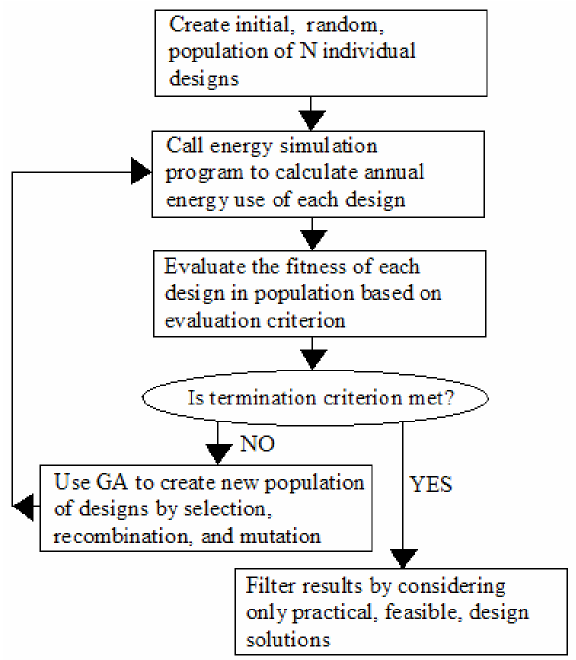

Figure 1: Flow chart of the optimisation tool

2.2 TRNSYS building simulation program

In order to evaluate each design configuration generated by the GA, a generic ZESH simulation model was developed in TRNSYS [7]. In the tool, there are inputs, constants, and parameters to be optimised. Since the design optimisation tool that is being developed is intended to be used in the early design stages, little information would be known about the design, which restricts the number of inputs that can be required. The following would be the only inputs a user would need to run the program:

Area: The desired floor area of the house;
Number of stories: Option of 1 or 2 storey home;
Orientation: Orientation of the house to be built, south is set as the default orientation of the front facade;
Energy target: The target for net-energy consumption;
Lot size: Lot size will restrict footprint of the house;
Electricity costs: Utility rates required to determine monthly energy costs;
Mortgage details: Financing costs required in determining monthly costs of energy upgrades; and,
Location: Desired location of the project is required in order to use the correct weather data.

There are certain parameters that will be kept constant for the prototype version of this tool in order to reduce the scope of the problem. In the future, once the benefits of this type of optimisation tool have been demonstrated, some of the constants could be either moved to inputs, or added to the variables that are being optimised. The constants include:

House type: One- and two-zone models are being considered. The two-zone model separates the house with a south-facing, high solar gain, zone and a north-facing zone;
Rectangular shape: Only rectangular floor plans are being evaluated;
HRV: An efficient heat recovery ventilator will be standard in all cases;
Zone height: a standard ceiling to floor height will be used;
Window shading: The same internal shading devices and controls will be used in all cases;
Control strategies: The same HVAC control strategies will be used in all cases; and,
Air tightness: Air tightness in the house will initially be set at levels found for airtight construction.

There are so many components used in constructing buildings, each having different configurations and technologies to chose from, all having different costs, that it is difficult to narrow the scope of variables that will be optimised. Table 1 provides a summary of the variables that will be optimised in this tool. Note that these are the values used at the initial stages of the research. Some parameters may be added, removed, or the allowable range and step size may change based on the results of a sensitivity analysis using the tool. Note that the amount of parameters, and their range and step size was limited in order to try to minimise the size of the solution space; the solution space is still quite large, 137,438,953,472, but is over 1.3 million times smaller than the one used in [8]. The following parameters will be optimised:

Form: A length to width ratio between 1 and 2 will be considered, but will be limited to the lot size;
Window type: Four window types ranging from 2- to 4-pane will be considered;
Window area: The window area will be calculated based on percentage of respective wall coverage, with south facing window having larger range;

Window overhang: Overhangs will be considered in all but north facing windows;
Wall construction: Eight different wall configurations will be tested comprised of walls with varying insulation using standard 2 x 6 stick frame, insulated concrete forms (ICF), and structural insulated panels (SIP). (RSI: 3.2 to 8.6, R18.1 to R48.8);
Thermal Mass: Additional thermal mass can be added by either adding an interior layer of bricks to the exterior walls, or by increasing the thickness of the concrete in the floor;
Heating system: Eight different heating systems will be considered initially: an air system with solar thermal and electric heater, a hydronic system with solar thermal and electric heater, an air-to-air heat pump, a ground source heat pump with air heating, a ground source heat pump with hydronic heating, a water-to-air heat pump using solar thermal and a desuperheater, a water-to-water heat pump using solar thermal, and a water-to-air heat pump using solar thermal;
Cooling system: Two options are available for cooling: 1) there will be no cooling, or 2) have cooling utilising the heating system's heat pump, if it exists, or with a regular sized efficient air conditioning system;
Thermal collector type: Both flat plate and evacuated tube solar thermal collectors will be considered;
Thermal collector area: Four sizes of solar thermal collectors will be considered; and,
Thermal storage volume: Four sizes of solar thermal tanks will be included.

Table 1: Summary of Variables to be Optimised

	Parameter	Minimum Value	Maximum Value	#
1	Length/width	1	2	8
2	Window type	2-pane	4-pane	4
3	N window area	5%	20%	4
4	E window area	5%	20%	4
5	S window area	10%	80%	8
6	W window area	5%	20%	4
7	E overhang	0 m	0.75 m	4
8	S overhang	0 m	0.75 m	4
9	W overhang	0 m	0.75 m	4
10	Wall construction	RSI 3.2	RSI 8.6	8
11	Thermal mass	Light	Heavy	4
12	Roof slope	Flat	21 in 12	8
13	Heating system	Low cost	High cost	8
14	Cooling system	None	Efficient	2
15	Thermal collector	Flat plate	Evac. tube	2
16	Collector area	4 m^2	16 m^2	4
17	Storage tank size	0.5 m^3	2 m^3	4

2.3 Genetic algorithm program

A GA program was selected that would serve as the base of the optimisation algorithm [9]. The program has been modified to function with the 17 parameters listed in Table 1. In addition, in order to accelerate the computational requirements of the program a subroutine was added that would store in memory all different configurations that are evaluated in order to avoid calling TRNSYS to calculate the same set of parameters more than once. Further modifications will be performed in order to make the GA program geared for this specific application. The GA program has been set such that it can call TRNSYS to evaluate the fitness of each individual using the Type70 module in TRNSYS that automatically updates parameters of all components at the beginning of each simulation. For cases where inputs need to be updated, an input file is updated and read into TRNSYS before every simulation. During the building simulation, key indicators are tracked, which are then sent back to the GA program to evaluate the fitness of a given design.

In terms of fitness, there is some difficulty associated with using energy consumption as the optimisation criteria for a ZESH. One would have to somehow ensure that the trivial solutions of adding large solar thermal collectors and sufficient PV panels to meet the loads of an inefficient house were not considered as having high fitness. The costs of the material will play an important part in determining the optimal ZESH. In 30 years, advances in PV may reduce their costs such that it does not make sense to spend large sums of money on energy efficiency, if electricity could be generated at low costs. In order to be able to include the cost of technologies in the optimisation, it was decided to use cost as the main optimisation criteria. The user simply inputs a target net-energy consumption and the optimisation tool finds cost effective ways of building it. There will be some constraints added to the problem. For example thermal comfort will be tracked, and designs that lead to unacceptable thermal comfort will be penalised to ensure that the space is within acceptable comfort ranges.

There is large potential in using costs as an optimisation criterion. Caldas [10] considered this concept in her thesis by evaluating energy efficiency using different wall construction materials. For a building in Phoenix, the energy level reduction was 6% on average compared to the random initial population; however, cost reductions were in the order of 41%. In Chicago, where building envelope design is more important in terms of energy efficiency, average energy consumption level decreased by 33% in relation to the initial random population, while the costs reduced by 68%. In order to save costs, lower performing and lower costing insulation materials were used in the south wall, but the north wall remained highly insulated. Results showed that for the same energy consumption, a wide range of costs could be obtained.

2.4 Electricity consumption and generation

One thing that needs to be considered when designing a zero energy house is the effect of behaviour on overall consumption. A given ZESH might be able to reach the zero energy target for a specific family of four that is more aware of their energy consumption, whereas it may be short by as much as 50% for a different family of four that pays no attention to the amount of energy they consume. In fact, "occupant effects" can result in an annual energy use ranging from 70 to 140% of the average use in commercial and residential buildings [11]. Consumption at the low range is half as much as on the high side. Studies in the US, the Netherlands, and the UK estimate that 26-36% of in-home energy use is due to resident behaviour [12]. Factors that influence consumption include the number of occupants, the average time spent at home by the occupants, the age of occupants, and feedback given to the occupants on their energy consumption.

Behaviour of the individual occupants also plays a significant role in having varying consumption. A study performed to determine the variation of energy used in cooking found up to a 50% variation in electricity consumption between six chefs, all cooking the same meal with the same equipment [12]. All these results show that there is promising potential in energy conservation that could theoretically be achieved by changing energy-using behaviour. However, for this first version of the optimisation tool, set consumption patterns will be used in all cases that were calculated based on occupancy of 2 parents with 2 children.

For lighting, consumption was calculated assuming a number of 13 W compact fluorescent light bulbs were present and set schedules for each were estimated. The resulting lighting load for the year came to 400 kWh. Major appliances in the house considered include: refrigerator, freezer, dishwasher, clothes washer, clothes dryer, and range. The load of each appliance was selected based on the average energy consumption of the top 10 appliances in each type from the EnerGuide database [13], resulting in a yearly consumption of 1940 kWh. Even though electricity use for minor appliances has been growing rapidly and is responsible for an ever increasing proportion of total household electricity use, this category of electricity consumption is only beginning to be studied, in part due to the lack of consensus of what the definition of a minor appliance should be [14]. For this study minor appliances and loads were assumed to consume 1,350 kWh per year. Finally, many major and minor appliances consume electricity when they are not in use, this is referred to as standby power consumption. A value of 107 kWh was used to cover these standby loads that may not have been considered in calculating other loads. The gains associated with each of these loads are released into the zone through a split between radiation and convection as recommended in [15]. As for the consumption of hot water, a set of realistic domestic hot water profiles developed for the Solar Heating and Cooling Program of the International Energy Agency, Task 26: Solar Combisystems was used [16].

No parameters of the photovoltaic panels will be directly optimised. The type and size of the required photovoltaic panels will be calculated based on the results of the generation of a 1 kWp size panel. The size (kWp) will be calculated in order to reach the desired net-energy consumption target. In the case of ZESH, the size of the panels will be calculated as follows:

$$kWp\ required = \frac{Total\ consumed\ electricity}{Total\ electricity\ generated} \cdot kWp$$

The type of panels will be selected based on the cheapest technology that will fit on the available roof area (total south-facing roof area minus solar thermal collector area). In reality, the PV could be mounted in locations other then a south-facing roof, such as the façade or even as overhangs. In addition, adding heat recovery to PV panels to form a PV/Thermal (PV/T) product could also bring some advantages. However, the design optimisation tool that is being developed is based on existing building integrated PV technologies. PV/T technologies are at their infancy and it would be difficult to include it as an option without knowing its true cost and performance. In an attempt to reduce the number of optimisation parameters, façade integration was not included based on the fact that this approach is very seldom used and no actual BIPV façade products exist to the knowledge of this researcher. PV overhangs were not included, as overhangs would generally not provide enough area to generate enough electricity to achieve the net-zero energy target. Therefore, overhangs would have to be added in conjunction with roof integrated PV, which is an option that could be included in future versions of the tool.

3. ANALYSIS

3.1 One-zone versus two-zone model

One of the drawbacks of using genetic algorithms is the computational time it takes to run through the optimisation. The level of detail and the simulation time-step used in modeling the house play a large part in establishing the time it takes to run the optimisation tool. GA have been shown to systematically find near optimum solutions of building optimisation problems that have large discrete search spaces (1.94×10^{22}) with as little as 300 evaluations of different building configurations [17]. Therefore, in comparing the approximate total calculation time of the optimisation tool, a total of 300 TRNSYS evaluations will be assumed. Table 2 shows the approximate time it takes to go through one yearly simulation of the one and two-zone TRNSYS models using a simple electric auxiliary air heater using different time steps, 200 m^2 floor area, Montreal weather data, and using a 3.2 GHz processor with 512 MB of RAM. Note the 2-zone results in the table are average results between having the south zone take up 25%, 50%, and 75% of the total floor area.

Table 2: Preliminary TRNSYS simulation results

Time Step (min)	1-Zone Run Time (sec)	1-Zone Heater (kWh)	2-Zone Run Time (sec)	2-Zone Heater (kWh)
60	15	15,680	268	17,313
30	28	14,685	407	16,568
20	38	14,680	483	16,393
10	72	14,615	619	16,446

It is apparent from Table 2 that there is a considerable difference in the time it takes for a yearly simulation of a one-zone model in comparison to a two-zone model. Running the simulation 300 times would take the one-zone model between 1.25 to 6 hours depending on the time step, and between 22 to 51.6 hours for the two-zone model. If it is found that more than 300 runs are required, or if multiple optimisation runs need to be effected, or if the more modeling complexity is added, the time difference between the using one and two zones can become very significant. In terms of computation time, it is evident that it would be preferable to use a one-zone model with larger time steps. However, it is imperative to further scrutinise the results in order to determine, which model and time step achieves a minimum level of accuracy required for this type of application. Since the fitness function of the GA will be highly dependent on energy consumption and thermal comfort, the results were further analysed to compare the predicted zone temperatures and calculated early energy consumption between the one-zone model and the two-zone model.

From Table 2 it can be seen that the two-zone model predicts an average heater consumption that is 11% higher than the one-zone model. One of the reasons for this is that the control strategy used in the two-zone model for those results used the lowest temperature between the south and north zone to initiate the heating. Since the one-zone model gives more of an average temperature between the two-zones, it can be deduced that using this control strategy for the two-zone model would result in higher calculated heating loads. A control strategy based on a mixed temperature between the south and north zone should provide closer results. Table 3 shows results comparing the results of the two-zone model and one-zone model assuming an even split between south and north zones and a time-step of 20 minutes. Three control strategies were used, one identical to what was used for results in Table 2, one using the mixed zone temperatures, and one based on controlling the heater based on the highest zone temperature. The table also provides the number of hours during the year that each zone was below 16ºC and 18ºC, and the number of hours that the zones were above 28ºC and 33ºC. The only cooling that is used is using outdoor air at 3 air changes per hour (ach) and 6 ach when the outdoor temperature is lower than the zone temperatures.

The results of Table 3 clearly show that using the mixed zone temperature for the two-zone heater control results in a much closer annual heating load to the one-zone model. In fact, the difference between the two went from the one-zone results being 11% lower than those of the two-zone to being 1.2% below. Provided that a mixed zone temperature is used for the heater control, the one-zone model is adequate for calculating the annual heating load. However, since the one-zone model is more of an average temperature between the zones, it averages out some of the peak temperatures and results in fewer hours in the year that the zone temperatures are outside the set thermal comfort range. To demonstrate the difference between the results, Figure 2 shows results for a one day period that demonstrates this tendency.

Table 3: TRNSYS control strategy results analysis

	1-Zone	T_{high} control	T_{mix} control	T_{low} control
Heater (kWh)	14,680	13,530	14,510	15,883
S_zone < 16ºC	n/a	212	5	4
S_zone < 18ºC	n/a	1,785	669	26
S_zone > 28ºC	n/a	294	297	299
S_zone > 33ºC	n/a	10	10	10
N_zone < 16ºC	n/a	104	26	0
N_zone < 18ºC	n/a	558	349	0
N_zone > 28ºC	n/a	150	150	150
N_zone > 33ºC	n/a	3	3	3
1-zone < 16ºC	0	n/a	n/a	n/a
1-zone < 18ºC	7	n/a	n/a	n/a
1-zone > 28ºC	191	n/a	n/a	n/a
1-zone > 33ºC	5	n/a	n/a	n/a

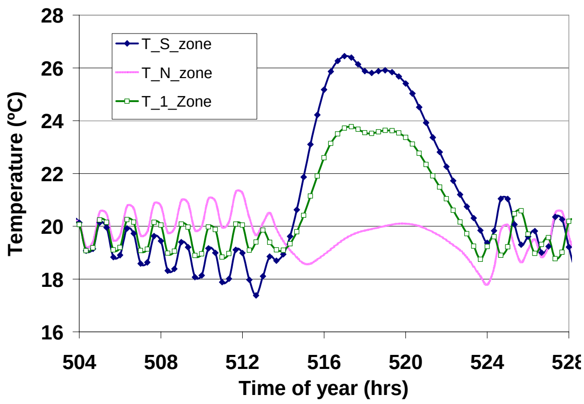

Figure 2: Comparison of predicted temperatures

4. NEXT STEPS

Based on the results presented above, the tool will be developed using the one-zone model. This will underestimate the thermal comfort, however, a multiplication factor will be determined based on results from the two-zone model results to account for this error. Cost data for the energy efficiency and renewable energy upgrades need to be obtained. The TRNSYS model also needs to be updated to include all heating and cooling systems. Once complete, the results of the building simulation model will be validated and then linked with the GA program to test the optimisation tool.

Given that this will be the first whole-house design optimisation tool based on genetic algorithms, significant important information will be able to be extracted from the results. Similarly to the analysis that was done on the number of zones, the impacts that other critical assumptions have on the results of the optimisation will be analysed. This will include a look at how the air flow is treated, the control strategies that are used, the setup of the GA program itself among other important elements. Once the program will be validated, it will be used to find what critical parameters affect the cost of low and ZESH the most. In addition, the tool will be used to develop new design guidelines (rules of thumb) for industry. The impacts of varying utility cost-structure on the cost-effectiveness of solar housing will be investigated.

Another important part of the research will be to validate the use of design optimisation tools. In order to do this, the results obtained by the optimisation tool will be compared to results obtained through traditional design practices. Designs from individual experts, and from groups of experts participating in a design charrette will be compared to the results obtained from the new tool. In addition, the tool will be used in an attempt to facilitate a design charrette. The charrette participants will be given results from the optimisation tool before the event in order to give them benchmark designs to begin with. They will then be able to start with an optimum design and add to it to meet the particular design requirements of the given project.

5. CONCLUSION

This paper discussed needs for a new generation of design tools that will assist designers in finding optimal configurations of low and net-zero energy solar homes. One such tool is presented in this study that utilises a building model developed in TRNSYS and a GA optimisation program. Current computer processing speeds limit the complexity of the models. For the presented building simulation model, a one-zone approximation will be used for the whole house, greatly reducing the computation time required to do a yearly simulation. As the processing speed of computers increases, greater modeling complexity could be accommodated. However, the current house model should give results with a sufficient level of accuracy for an early stage design tool, which is the intended use of the tool.

With our society's increasing environmental awareness, and the requirements imposed on many countries due to the Kyoto accord, there is no doubt that ZESH will one day become prolific, the development of new technologies, and new tools will only help to hasten its wide spread acceptance.

ACKNOWLEDGEMENT

Financial support for this collaborative research project was provided in part by Natural Resources Canada through the Technology and Innovation Program as part of the Climate Change Plan for Canada and through scholarship from the National Science and Engineering Research Council of Canada.

REFERENCES

[1] Charron, R. *A review of low and net-zero energy home initiatives* (2005) cetc-varennes.nrcan.gc.ca/fichier.php/41665/2005-133_e.pdf
[2] Caldas L., Norford L., A design optimization tool based on a genetic algorithm. *Automation in Construction* **11**, (2002) 173-184.
[3] Coley D., Schukat S., Low-energy design: combining computer-based optimisation and human judgement. *Building and Environment* **37**, (2002) 1241-1247.
[4] Kalogirou S., Optimization of solar systems using artificial neural-networks and genetic algorithms. *Applied Energy* **77**, (2004) 383-405.
[5] Grierson D.E., Khajehpour S., Method for Conceptual Design Applied to Office Buildings. *Journal of Computing in Civil Engineering* **16**, (2002) 83-103.
[6] Wright J., Loosemore H., Farmani R., Optimization of building thermal design and control by mutli-criterion genetic algorithm. *Energy and Buildings* **34**, (2002) 959-972.
[7] Beckman, W.A., *TRNSYS A transient system simulation program*, TRNSYS Manual, Version 5, Solar Energy Laboratory, University of Wisconsin, (2000) Madison USA.
[8] Wetter M., Wright J., A comparison of deterministic and probilistic optimization algorithms for nonsmooth simulation-based optimisation. *Building and Environment* **39**, (2004) 989-999.
[9] Carroll, D., FORTRAN Genetic Algorithm Driver, http://cuaerospace.com/carroll/ga.html
[10] Caldas L., *An evaluation-based generative design system: using adaptation to shape architectural form*, MIT Press, (2001) Ph.D. Thesis
[11] Chiras D. *The Solar House: Passive Heating and Cooling.* Chelsea Green Publishing.Vermont, (2002), 274 pp.
[12] Wood G., Newborough M., Dynamic Energy-Consumption Indicators For Domestic Appliances: Environment, Behaviour And Design, *Energy and Buildings* **35**, (2003) 821-841.
[13] http://oee.nrcan.gc.ca
[14] Herring, H., Electricity Use in Minor Appliances in the UK, *Energy* **20**, (1995) 705-710.
[15] McQuiston, F., J. Parker, J. Spitler, *Heating, Ventilating, & Air Conditioning: Analysis and Design*, 6th ed., (2005), John Wiley & Sons, Hoboken, US.
[16] Ulrike, J., V. Klaus, *Realistic Domestic Hot-Water Profiles in Different Time Scales*, V.2.0, (2001), Universität Marburg.
[17] Wright J., Alajmi A., The Robustness of Genetic Algorithms in Solving Unconstrained Building Optimization Problems, Proceedings of Building Simulation '05, Montreal, Canada, August 2005, 1361-1368.