ROBUSTNESS STUDY OF A FLEXIBLE ZERO-ENERGY HOUSE

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ABSTRACT

The U.S. Department of Energy launched the 5th Solar-Decathlon-competition, defying student teams from all over the world to conceive a house powered exclusively by the sun. Team Belgium, of Ghent University, conceived the E-Cube, a modular and flexible house, that could be adapted depending on the inhabitants, the building site and the climate. This paper focuses on that last aspect: the robustness and flexibility of the energy concept and the design, depending on the climate it is built in. Different climates are selected for the analyses, reaching from climates with extreme winters (Canada: Saskatoon) to arid climates (US: Las Vegas), through milder climates (Belgium: Ukkel and US: Washington D.C.). To cover both locally (Belgian) and internationally used energy-assessment procedures both the Flemish EPB-software as well as the PHPP-software are used. Furthermore, dynamic simulations in Trnsys are carried out to obtain more detailed and accurate feedback on the buildings' dynamic thermal response. Through simulations with these three calculation methods, energy robustness is tested and alternative solutions for the building envelope are proposed, adapting the building to its boundary conditions. This paper presents the results from this study, analyzing the differences due to the climate, the calculation method and the design options.

1. FRAMEWORK & BACKGROUND

Solar Decathlon

Every two years since 2002, the U.S. Department of Energy launches an international competition for university students to design, build and operate a solar-powered house: the Solar Decathlon contest [1]. After different selection procedures, 20 student teams from all over the world are invited to further develop their initial design and to build a prototype on the National Mall, in

Washington D.C. (USA), to participate in the final competition phase. During that phase, the building and its operation, performed by students, are submitted to real-life testing challenges. The projects are evaluated both through their project proceedings as well as through the results from those tests, on different levels reaching from energy and comfort performance to economics, architectural quality…

Team Belgium & the E-Cube

While the final competition will take place with the houses being built and tested in Washington D.C. in September 2011, Team Belgium, of Ghent University, wanted to take over the 'global' character of the competition more literally: they conceived a modular and flexible house, that could be adapted depending on the inhabitants, the building site and the climate, the E-Cube [2]. Increasing its own constraints, Team Belgium aimed at keeping the house within a reasonable budget. Modularity and standardization with low complexity, while increasing flexibility, are not the only concepts chosen for budget management and robustness. As the competition aims at solar-powered designs, lowering the net heating and cooling demand is an important requisite for reducing the expenses for HVAC- and PV-systems, but it is difficult to achieve this in different climates within one design concept.

While the competition doesn't require any analysis of the building in other forms or under other conditions than its final built 'competition design' in Washington, Team Belgium's statement of the E-Cube's flexibility needed to be analyzed for reasons of optimization as well as to prevent it to become a mere theoretical concept statement.

On aspects of energy demand and comfort level, thermal simulations are needed to investigate adaptability of the basic design to other climates. This paper focuses on this thermal robustness and flexibility analysis, analyzing both heating and cooling demands in different climates.

E-Cube Washington

The E-Cube in its competition format comprises all the necessary space and facilities for a single family with 1 or 2 children in compliance with the demands of the Solar Decathlon competition. The functions are spread over two levels: the ground floor containing the 'day area' (living room, kitchen, toilet) and technical room and the first floor accommodating the 'night area' (bedrooms and bathroom).

Both floors are intimately connected by voids. These considerable voids have to be kept in mind while analyzing the energy demand of the house, normalized to the net, inside usable floor area of 81,2m². While these voids might be taken as a matter of debate from purely energetical or economical points of view, they render a pleasant sense of open space within this compact volume with low ceilings.

The modularity of the concept is mainly materialized by the use of a standard metal framework as the structural skeleton, covered with prefabricated sandwich-panels and windows of standardized dimensions. The ground floor also consists of sandwich panels, mounted on scissor jacks, limiting the precision, work and material needed for the ground leveling.

As sun irradiance on southern facades are high in winter in Washington D.C., the south facade includes the most windows to increase solar heat gains. The technical space, bathroom and toilet are north oriented.

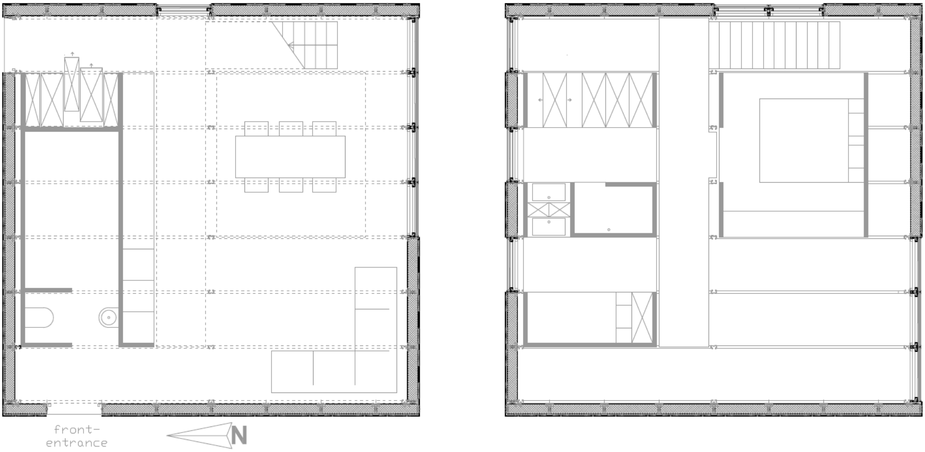


FIG. 1: GROUND FLOOR (LEFT) AND FIRST FLOOR (RIGHT) OF THE E_CUBE (TEAM-BELGIUM)

2. ANALYSIS SET-UP

Climates

The energy and comfort performance of a house largely depends on the boundary conditions it has to stand up to. Therefore, the selection of the outdoor climates will have a major impact on the findings from the analyses. To obtain sufficient insights on the robustness of the E-Cube's concept to climatic differences, without losing the necessary sense of reference, while covering a broad variability of climatic conditions, four climates are selected. As Team-Belgian has its roots in its local architecture-educational framework, selecting the Belgian climate (reference city: Ukkel) is an obvious necessity, both to serve as a well-known reference point as to make comparison possible with results from the local governmental energy performance calculation software. The E-Cube, in its basic design variant, will be built and tested in

Washington D.C. for the competition. Therefore, Washington's climate was the second obvious choice. While neither can be considered as extreme (nor for summer nor for winter conditions), they show important differences with regards to their yearly temperature and sun irradiance profiles. While average temperatures during the heating season are roughly similar, solar gains in Washington D.C. are higher than in Ukkel, not only on average over the whole year, but especially so on the south side during winter.

To include more extreme climates both for heating as for cooling loads, the climates of Saskatoon (Canada) and of Las Vegas (USA) were selected. While Las Vegas resides in a subtropic arid climate, challenging mainly the cooling demand, the climatic conditions of Saskatoon are much more complex. The 'humid continental' climate of Saskatoon has both relatively warm and sunny summers as well as very cold winters, increasing the designer's challenge to find the right equilibrium between heating and cooling loads while keeping the total yearly consumption low.

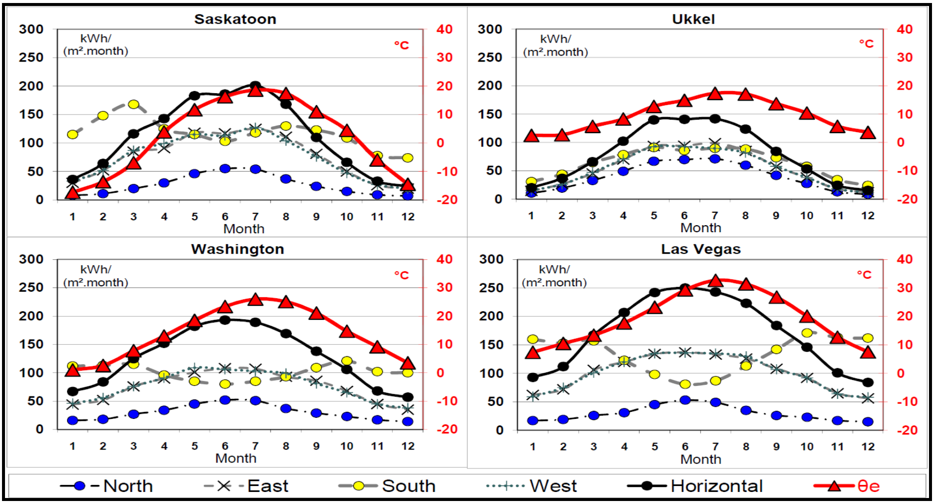


FIG. 2: CLIMATE CHARTS (SASKATOON, UKKEL, WASHINGTON D.C., LAS VEGAS ; MONTHLY CUMULATED SUN IRRADIANCE [kWh/(m^2.month)] & MONTHLY AVERAGE TEMPERATURE [℃]) (PHPP 2007 [6])

Software

Appropriate assessment tools and criteria have to be selected for the robustness analyses. As the building isn't oriented solely towards the Belgian or European market, the Flemish EPB-software [3] isn't enough. Team-Belgium chose to aim at the zero energy-goal by implementing the basic passive house principles first, as reducing the net heating and cooling demand is a crucial step to reduce the high expenses of the HVAC-appliances and PV-panels. Because of this design prerogative, the more international character of the calculation sheets of the Passive House Platform ('PHPP-software') and its relatively simple use for primary estimation of net heating and cooling demands, the PHPP (v.2007) [6] is selected for the basic sensitivity and flexibility analyses. To obtain more detailed information on the buildings dynamic response to the outdoor environment, some simulations are performed with the dynamic simulation software Trnsys [5]. While more sensitive to the user's knowledge and expertise, such simulations can deliver higher accuracy for the assessment of energy use (energy consumption and peak loads) and indoor climate (in winter and summer conditions).

Simulation assumptions and standardization

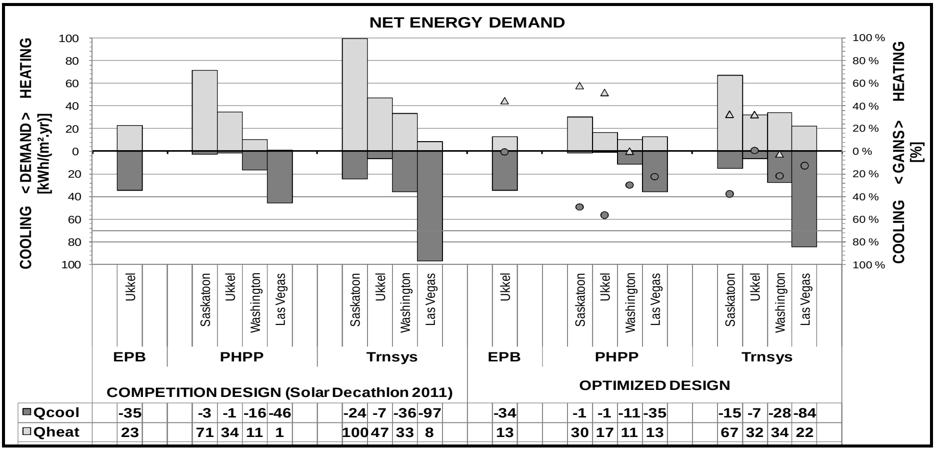
To compare results from the three software programs, knowledge of their main differences is needed. While Trnsys allows full user input on building parameters and boundary conditions for dynamic simulations, EPB and PHPP are mainly conceived for certification purposes based on simplified quasi steady state calculation principles under standardized conditions. While the EPB software cannot be tweaked, formula and fixed values within the PHPP-spreadsheets and Trnsys can be fitted to comparable grounds. In this paragraph, some of the main differences relevant for this case study are analyzed for the E-Cube. While it is not the goal of this project to analyze the differences in detail or to aim at a full fit between the software programs, the most influencing factors have to be taken into account.

Two important differences can be identified between the interior boundary conditions of EPB and PHPP. The average interior set point temperatures for heating and interior heat gains per square meters floor area for the E-Cube reach 18℃ and 5,36W/(m².K) in EPB [4]. In the PHPP , they value respectively 20℃ and 2,1W/(m².K). While the choice of these assumptions can be questioned, depending e.g. on different buildings and their use, the PHPP-values are considered more applicable for the E-Cube due to its high comfort aim and energy performance, both of the building as well as of the technical appliances. Therefore, these values are also used in the final Trnsys-simulation. For the calculation of the cooling loads, a set point temperature of 25℃ (inside) is considered, as is in PHPP.

The hygienic ventilation rate in EPB is calculated based on the buildings' exterior volume, resulting for the E-Cube in 163,48m³/h [4]. In PHPP, the design value is defined as the maximum between the needed exhaust rate based on the 'wet' rooms and the needed pulse air based on the amount of inhabitants (based for certification on the net floor area), resulting in 120m³/h. Within the PHPP-method, this value can be reduced to 70m³/h for the heating calculation. Nevertheless, in Belgium, the design ventilation rate has to comply with the local ventilation standard [8], resulting in 150m³/h for the E-Cube. In practice however, field research [7] indicates that the average ventilation rate found in mechanically ventilated houses, due to the user settings, can statistically be assumed to be 54% of the design value, resulting in 81m³/h. In the Trnsys-simulations, 81m³/h is assumed, except when the bypass is activated to cool the house at full design rate (150m³/h).

The infiltration rates also differ between EPB and PHPP. Within the EPB-method, the measured air leakage at 50Pa pressure difference is divided by a fixed factor of 25. Within the PHPP-method, the buildings specific wind exposure is taken into account, resulting for the E-Cube (for n50=0,5/h) in a reduction factor between 7,6 (no wind shading) and 19,1 (high wind shading).10,9 is the reduction factor obtained in PHPP for 'mild' wind shading and is used here both in the PHPP and Trnsys simulations.

The implementation of sunshades in the cooling load calculations in EPB and PHPP differ greatly. This is due to the assumption made on their usage by the inhabitants or the automated control system. While, for automated solar shadings, PHPP takes no time use factor into consideration in the cooling demand calculation (considering the sunshade is permanently active during the cooling season), EPB considers a use factor of 50% within the calculation of the cooling loads. These values represent extreme values, none of which are representative for a well designed automated system. In the Trnsys simulations, the sun shading is activated when both the perpendicular sun irradiation exceeds 200W/m² and the inside temperature beyond 21℃, anticipating the need for cooling.



	EPB Ukkel	PHPP Saskatoon	PHPP Ukkel	PHPP Washington	PHPP Las Vegas	Trnsys Saskatoon	Trnsys Ukkel	Trnsys Washington	Trnsys Las Vegas	EPB Ukkel	PHPP Saskatoon	PHPP Ukkel	PHPP Washington	PHPP Las Vegas	Trnsys Saskatoon	Trnsys Ukkel	Trnsys Washington	Trnsys Las Vegas
■ **Qcool**	-35	-3	-1	-16	-46	-24	-7	-36	-97	-34	-1	-1	-11	-35	-15	-7	-28	-84
□ **Qheat**	23	71	34	11	1	100	47	33	8	13	30	17	11	13	67	32	34	22

FIG. 3: NET ENERGY DEMAND (BARS: LEFT Y-AXIS) & GAINS AFTER OPTIMIZATION (RELATIVE TO THE COMPETITION DESIGN, DOTS: RIGHT Y-AXIS) FOR HEATING (UP) & COOLING (DOWN)

FIG. 3 shows the effect of these simulation assumptions and standardizations on the calculated heating and cooling loads (on the left side for the original competition design). Comparing the results for Ukkel between the EPB and PHPP, the higher heating load and much lower cooling load in PHPP is noticeable. While the heat transfer coefficient due to transmission is equal in both calculations, the increased temperature difference causes higher transmission heat losses in the PHPP heating calculation. The ventilation heat losses in winter differ less, due to the higher ventilation rate considered in EPB. With regards to the heat gains, even though the solar heat gains during winter are higher in PHPP, the much lower internal heat gains from PHPP have more effect on the total heat balance for heating. This has the opposite effect on the cooling load, further increased by the much higher solar heat gains from EPB due to the low use factor for the automated solar shadings. While for other buildings, results might differ, effects of the internal heat gains, use factor for sun shading, internal temperature set points and ventilation rate during winter will have significant impacts upon the results, especially for highly insulated and sun orientated buildings.

The net heating and cooling demands obtained in Washington D.C. are low, with a higher value in summer, coinciding with higher solar irradiance on the PV-panels on the E-Cube’s roof. For Saskatoon and Uccle, lowering the energy consumption should be achievable by lowering the heat loads. On the other hand, for Las Vegas, the challenge is to lower the cooling load.

Further sensitivity analyses in the following paragraphs are carried out with the official PHPP-calculation method to be comparable to certification criteria. The PHPP2007 is only tweaked in its cooling load calculation, to take into account the use of the heat recovery system with lowered ventilation rate during extreme summer periods if the outdoor temperature exceeds the indoor temperature.

3. ROBUSTNESS ANALYSIS & OPTIMIZATION

Sensitivity analysis

The ‘Washington’-design, as conceived for the competition, is taken as a starting point for the sensitivity analysis. The competition design resides on some modular principles, making both standardization possible as well as adaptations of the components and to their use within the building, taking into account the local boundary conditions. Therefore the analysis starts by identifying the main flexible parameters of the building. For each of those parameters, besides the value or option selected for the competition proposal, realistic extreme values are defined to serve as the boundaries of the E-

Cube’s flexibility. (TABLE I) The choice of these extreme values has to be kept in mind while analyzing the results.

A one-at-a-time sensitivity analysis is performed for each of those parameters under the four climatic conditions: for each parameter, a calculation is performed with the reference and with both extreme values, leaving all other parameters unchanged. The results are shown in FIG. 4, where the difference for heating and cooling demands are indicated in comparison to the base-case, the competition design, illustrating the added gains or losses achievable by changing the separate parameters for the different climates (left to right: Saskatoon, Ukkel, Washington D.C., Las Vegas). Showing both heating and cooling demands separately allows for more sensible analyses of the results for optimization purposes. The optimization should aim both at reducing the total energy demand as well as at leveling out the energy demand over the year, with regards to the dimensioning of the HVAC-appliances and PV-system as a solar-powered house on budget is the ultimate goal.

Parametric changes lowering heating demands generally increase cooling demands (and vice versa) thus challenging the designer to find the right balance. Nevertheless, some systems are not confronted with that duality. Well-controlled, automated solar shadings should act only in summer conditions (e.g. based on solar irradiance and indoor temperature measurements) and the heat recovery system is bypassed during summer, except when the outside temperature is higher than the inside temperature (Las Vegas). Other parameters also have that duality, but only to a very limited extend. The thermal insulation level of the envelope (Ug and insulation thickness of the sandwich panels), even though of extreme influence on the heating demand, has relatively low impact on the cooling demand. This is caused by the overruling influence of the heat gains (internal and sun) and the much higher heat exchanges through ventilation due to the bypass during summer. Furthermore, lowering the insulation level in Las Vegas (panel insulation, Ug, Uf and air tightness), has a negative, indeed almost negligible, effect both on heating as on cooling demands as the outdoor temperature in summer exceeds the indoor cooling set point temperature (25℃).

When analyzing the influence of the glazing and windows, it has to be reminded that all glazing in the base case, except the outward turning front door on the left (west) side, is considered to have proper, automated external sun shading, only active during the cooling period. Nevertheless the good shading, increasing the window area’s always results in higher cooling loads due to the added solar gains, even though it also results in an increase of the transmission losses. Only for the south (right) façade, an increase in window area decreases the heating loads due to higher solar gains.

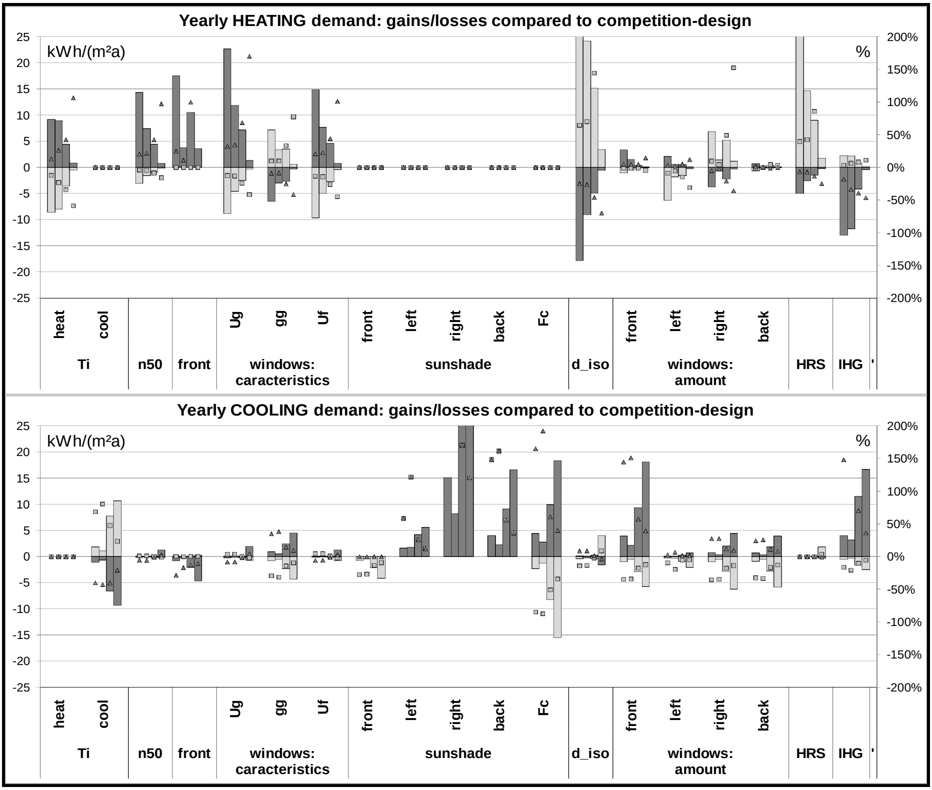


FIG. 4: ONE-AT-A-TIME SENSITIVITY ANALYSIS: GAINS & LOSSES IN COMPARISON TO THE COMPETITION DESIGN: RESULTS FOR EACH PARAMETER FROM LEFT TO RIGHT: SASKATOON, UKKEL, WASHINGTON D.C., LAS VEGAS (BARS=ABSOLUTE DIFFERENCES ON LEFT AXIS // DOTS=RELATIVE DIFFERENCES ON RIGHT AXIS) (LIGHT GRAY=LOWER VALUES // DARK GRAY=UPPER VALUES)

	Ti		n50	front	windows: caracteristics			sunshade					d_iso	windows: amount				HRS	IHG
	heat	cool			Ug	gg	Uf	front	left	right	back	Fc		front	left	right	back		
	[°C]	[°C]	[m³/(yr.m³)]	[-]	[W/(m².K)]	[-]	[W/(m².K)]	1/0	1/0	1/0	1/0	[-]	[m]	[-]	[-]	[-]	[-]	[-]	[W/m²]
ref.	20	25	0.6	W	0.6	0.6	1.16	N	Y	Y	Y	0.25	0.18	1	4	7	3	72%	2.10
low	18	23	0.3	(W)	0.4	0.5	0.6	Y	-	-	-	0.04	0.10	0	1	4	0	0%	1.58
up	22	27	2	(S)E	1.1	0.7	2	-	N	N	N	0.45	0.26	4	5	9	5	85%	5.36
Sask.	20	25	0.3	W	0.5	0.7	0.6	N	Y	Y	Y	(0.04)	0.26	1	1	9	3	85%	2.1
Ukkel	20	25	0.6	W	0.5	0.7	0.6	N	Y	Y	Y	(0.04)	0.26	1	4	7	3	85%	2.1
Wash.	20	25	0.6	W	0.6	0.6	1.16	N	Y	Y	Y	(0.04)	0.18	1	4	7	3	72%	2.1
Las V.	20	25	0.6	W	1.1	0.5	1.16	Y	Y	Y	Y	(0.04)	0.10	1	4	5	2	72%	2.1

TABLE I: PARAMETERS OF THE SENSITIVITY ANALYSIS: REFERENCE VALUE FROM COMPETITION DESIGN, EXTREME VALUES (‘LOW’ AND ‘UP’) AND OPTIMIZATION VALUES (SASKATOON, UKKEL, WASHINGTON D.C., LAS VEGAS) (FRONT FACADE ORIENTATION: LOWEST HEATING DEMAND=WEST, LOWEST COOLING DEMAND=SOUTH OR SOUTH-EAST)

In general, higher gains and losses are obtained when the demand from the reference case is higher (e.g. heating demands: Saskatoon > Ukkel > Washington D.C. > Las Vegas, as opposed to cooling demands: Las Vegas > Washington D.C. > Saskatoon > Ukkel). Nevertheless, some exceptions have to be noted. While the total heating demand is much higher in Saskatoon than in Ukkel, changing the heating set point temperature by 2℃ has a similar influence in both climates. The reason lies in the origin of the difference in heating demand between these two climates, caused mainly by the much lower temperatures reached during winter in Canada, while the length of the heating period remains almost unchanged for the E-Cube. As the cumulated heat losses are merely a product of the heat transfer coefficient and the temperature difference, integrated over time, as long as a different setpoint temperature doesn't considerably alter the length of the heating period, it will result in a similar energy gain, regardless of the outdoor temperature. This is the case, for the competition design of the E-Cube, when comparing Saskatoon with Ukkel. Another important exception can be found in the influence of the amount of south facing windows on the heating demand. The much lower influence in Ukkel compared to both Saskatoon and Washington D.C. (while heating demand is lower in Washington D.C.), originates from the lower southern sun irradiance during winter in Ukkel.

Optimization

A sensible balance was found in the competition design for the climate in Washington D.C. (between heating and cooling demand and between investment cost and building performance). For the other climates, the calculated energy demands and the sensitivity analyses show that better configurations can be found within the E-Cube's concept, design and building system. In this paragraph, an optimization is proposed based on the sensitivity analysis and the results are presented. While complete reorientation of the building or conceptual changes such as pergola structures for sun shading might be reflected on, it has been chosen to remain true to the design concept of the E-Cube and to keep also the basic configuration unchanged, to make a sensible analysis of the robustness of the design itself possible. The values chosen for each parameter in the optimized configurations are listed in TABLE I. For all climates, sun shading has been optimized. As the sun shading is already relatively good, the next step would be fully opaque shadings. This is only placed on the windows on the first floor, to keep a minimum visual interaction between inside and outside from the living room, lowering the chance for the user overriding the sunshades' automated closing. This is the only optimization proposed for Washington's climatic conditions.

For Saskatoon, emphasis is put on increased insulation levels, higher air tightness, better heat recovery system (HRS), decreased glazing area on the left (north) façade and increased glazing area on the right (south façade).

For Las Vegas, insulation levels are lowered while the sun shading is increased. The window areas on the south and east façade are also lowered. The heat recovery system, while of limited use in the competition design in Las Vegas, is kept in the optimized Las Vegas variation, where its relative importance on the heat losses during extremely hot summer periods increases due to the cancellation of the triple glazing. Furthermore, the heat exchanger itself ads only relatively limited cost and changes within the E-Cube's total design and ventilation system.

While the results in Ukkel are already satisfactory, some changes with limited effect on the architecture are made to see which performance can be reached under the competitions' 'visual' aspect. Therefore, the insulation is increased (Ug, Uf and insulation thickness) and a heat recovery system with higher efficacy is chosen.

The results of the optimized configurations for each climatic zone, calculated with the three software programs, can be found in FIG. 3 (right side).

For Saskatoon and Ukkel, reductions of the heating demand of respectively 58% and 52% are obtained, while reducing the cooling demand by respectively 49% and 56%, thus reaching very low energy standards in Saskatoon and (nearly) passive standards in Ukkel (PHPP). The reduction of the cooling demand from EPB in Ukkel is negligible, due to the low use factor of the shading, resulting in high absolute cooling loads and low relative gains from the better shading on the first floor. While the energy consumption according to Trnsys remains higher than according to PHPP, the gains remain important.

The improved sun shading on the first floor is enough in Washington D.C. to lower the cooling demand to the same amount as the heating demand, on a yearly basis, further leveling out the energy load over the whole year.

For Las Vegas, a new balance is obtained, with increased heating demand and lowered cooling demand. This levels out the energy load to some amount, but the energy demand remains high due to the long and hot cooling season, stressing the need for a further adaptation of the design or the buildings' total orientation in this extremely arid climate.

4. CONCLUSION

Team-Belgium developed, within the framework of the Solar Decathlon 2011, the E-Cube, a flexible zero-energy-house. The robustness of this adaptable

design has been tested through sensitivity analyses, resulting in component optimizations depending on the climate. Further insights were gathered on the sensitivity of different components of the E-Cube, the importance and effects of climatic differences and the influence of different calculation methods.
Special care has to be taken when extrapolating the findings from this and other sensitivity analyses to other projects, as many of the findings are not purely related to the parameter (component) changes and the relation between indoor and outdoor environment, but also to the total heat balance of the building. As such, the parameter combination of the base case impacts upon the sensitivity of the different parameters within the whole. Much more statistical analyses and simulations are needed to correlate all parameters for precise extrapolations. Nevertheless, this was not the goal of this paper, which aimed at adapting and optimizing a specific building concept and design to different climatic conditions.

5. AKNOWLEDGEMENTS

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