REACHING NET ZERO ENERGY: OVERCOMING CLIMATE CHALLENGES WITH A 'SOLUTION SETS' DESIGN APPROACH

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ABSTRACT

The paper proposes an innovative energy performances evaluation and design approach, developed during the II° Ph.D. IEA Task 40 Summer School. The aim of the work is to check the importance of a 'design with climate' approach in understanding how much climate conditions can influence the design choices. The idea is to focus on the technical and architectural solutions that have the highest impact on the overall energy performances of the building in its original climate, then to move it to a completely different location, re-evaluating the energy performances of the building, in connection to the new site challenges. The last step is a re-design study in order to achieve the best performances in the new location.

INTRODUCTION

In the context of the joint implementing agreement of the programs Solar Heating and Cooling (SHC) and Energy Conservation in Buildings and Community Systems (ECBCS) SHC Task 40-ECBCS Annex 52 of the International Energy Agency (IEA) "Towards Net Zero Energy Solar Buildings", the concept of Net Zero Energy Buildings (Net ZEBs) is being extensively analyzed in order to establish a shared point of view between experts in the field (Napolitano et al., 2012).

Task40 deals with the review and analysis of existing Net ZEB definitions and data also with regards to the grid interaction and energy mismatch analysis (Salom et al., 2012).

Other core objectives of the Task 40 are linked to the development and testing of innovative, whole building solution sets for cold, moderate and hot climates with exemplary architecture and technologies that would be the basis for demonstration projects and international collaboration. These objectives are leading towards developments and assessments of case studies (Doiron et al. 2011; Cellura et al. 2011, Garde et al. 2011). and investigations of advanced integrated design concepts (Hachem et al. 2012) and technologies in support of the case studies.

Task 40 also aims to identify and refine building design approaches and tools. This objective is achieved through the documentation of processes and tools (Cellura M. et al., 2005A, 2005B) currently being used to design Net ZEBs and under development by participating countries, while stressing gaps, needs and problems in the modeling.

The two levels of complexity of Net ZEBs, namely interaction of the building as a whole with the surroundings and the definition of technical solutions able to enhance the performances of the building inside the system boundaries, define the core efforts needed in the design process of Net ZEBs. This duality is mirrored in the definition of "Solution sets", developed in the context of Task 40.

A solution set can be interpreted as a technical, architectural element that allows the overall system to face its design challenges, e.g. lowering thermal loads peaks, face rigid climates etc. At the same time it is clear that a building, as a whole, can be considered a solution set, considering it as a unique system, designed in order to overcome the challenges that the climate, occupants' behaviour and the location all contribute to define.

The work presented by the authors is inscribed in the context of the Task 40 and, in detail, has been largely developed during the IInd International Energy Agency (IEA) Task 40 Summer Ph.D. workshop that was held in Cargèse (Corsica) in September 2012. The study focuses on the thermo-physical analysis of one of the six residential case-studies proposed at the summer school (EnergyFlexHouse) and its redesign. The proposed design strategy, in its first stage, aims to analyze the incidence of the most important solutions of the original case-study on the energy performances of the building. The second level of analysis focuses on the adaptation of the old building into a new climate: from the cold dominated climate of Copenhagen to the tropical one of La Réunion Island.

METHOD

The case study

The EnergyFlexHouse is located in Denmark, around 20 km from Copenhagen. It consists of two single-family houses of around 216 m^2 of heated area each and is in operation since fall 2009. The buildings are constructed on two levels: the kitchen and a big living room are located on the upper floor while the bedrooms, bathrooms and technical zones are in the ground level. The buildings aim at very low energy consumptions through the use of energy efficient equipment and appliances in combination to passive design solutions and heat recovery systems.

All the walls in the building comprise a core insulated wooden frame structure: the U value of the vertical construction elements is around 0.08 W/m^2 °C, the roof has a U value equal to 0.09 W/m^2 °C and the ground floor value is 0.01 W/m^2 °C. The average U value for windows (triple glazing) is around 0.75 W /m^2 °C and the average leakage rate is around 0.42 l/(s×m^2) at 50 Pa. The compact form (High volume/surface ratio), strategically placed windows in order to minimize electrical consumption for lighting, mobile solar shadings and natural ventilation strategies during summer are other passive techniques that have been largely applied to the EnergyFlexHouse.

Figure 1 The EnergyFlexHouse

The Net zero energy target is achieved through the photovoltaic (PV) system mounted on the roof south oriented. The PV panels, tilted at 55°, cover an area of 60 m^2 and yield more than 150 kWh of final energy per year and m^2 of heated floor (around 1100 kWh per year and m^2 of PV).

The domestic hot water needs are covered by a solar thermal system (4.8 m^2 on the south oriented, 55° tilted roof) and a heat pump: both systems are connected to a 180 l storage tank. Heating needs are handled by a ground/water source heat pump with a nominal 3.5 COP (at maximum load) connected to a radiant floors and radiators heat delivery system.

The Solution sets method

The study has been developed through the use of Energy Plus models that were created by the IEA task 40 subtask C members. The main aim of the summer school was not to enhance the modelling capabilities of the participants: instead, the idea was to have the possibility to brainstorm new concepts and ideas without worrying about technical-related issues. The study does not aim to obtain an instrument able to model with the best possible resolution the case study examined. The aim of the authors was to apply a new analysis approach, in order to show that the design of Net ZEBs cannot be developed if not in conjunction with a site analysis and multidisciplinary bioclimatic approaches. The study will be therefore conducted with the use of a simplified tool able to foresee trends at an early stage of design modeling resolution.

The first step of the study focuses on the assessment of the energy performances of the building.

The energy loads are estimated fixing heating and cooling set points, namely 18°C and 26°C; a Givoni (Givoni, 1992) comfort analysis has also been developed by running the base building model in free-floating mode.

Considering, at this stage, the solution set definition connected to the single architectural and technical elements, and not to the building as a whole, the idea is to “reduce” or “increase” (accordingly) the impact of the aforementioned solutions, in order to assess their incidence on the overall energy requirements in terms of final energy and ideal thermal loads.

In order to assess the importance of ventilation, as an example, the number of air changes per hour (ACH) has been set to nearly zero. The results of this kind of analysis have been compared to the baseline scenario, in terms of energy requirements / m^2 year and of percentage of comfort hours on the total for a year, to check the importance of each solution in overcoming the typical challenges of the Danish climate. Once the solutions have been analysed in detail in the climate of Copenhagen, the next step is the simulation of the base building in the tropical climate of La Reunion: it has been imagined to physically detach the EnergyFlexHouse ‘as it is’ from Denmark and put it on the new location.

The first part of the La Réunion section of the work is again the assessment of the comfort level and of the energy performances of the building: in other words it is a way to estimate the incidence of a completely different climate challenge to a solution set (the whole building) specifically designed to be effective in another context.

The next section of the work is the definition of the most important solutions that may be effective in the different climate. In this way, a new set of solutions will be evaluated following the previously described scheme, up to a ‘best case’ that would involve all the most impacting solutions and be the final target of the study.

Table 1
Average monthly temperatures [C°] (T) and horizontal radiaton [W/m^2] (HR) for the two sites. Source: Energy+ weather files

	Denmark		***La Réunion***	
	T	**HR**	**T**	**HR**
Jan	1	25	26	665
Feb	0	44	27	608
Mar	2	70	25	515
Apr	6	90	25	535
May	11	110	23	473
Jun	14	116	21	445
Jul	16	111	21	427
Aug	17	106	21	516
Sep	12	76	21	609
Oct	9	54	22	578
Nov	5	28	24	613
Dec	1	20	25	672

The work has been developed in accordance to the framework analysed in Task 40. The proposed methodology has allowed to jointly develop traditional approaches (bioclimatic, design with climate) to the most recent Net ZEB ones, where the bioclimatic needs are connected to the need to maximize energy generation. The importance of climate and site choice in accordance to the same methodological framework has been assessed.

Most likely, the best solution sets that will be identified for La Réunion, will be completely different from the ones that were effective in Denmark, because, as table 1 shows, the two climate are different (e.g. average temperature in La Reunion higher at least 6-7 °C than the Denmark one).

Modelling the EnergyFlexHouse

The EnergyFlexHouse has been simulated in its original Danish configuration, and the main results will be now presented.
The main Net ZEB balance definition that is presented in (Napolitano, A. et al. 2012) is described in equation 1:

$$|WeightedSupply| - |WeightedDemand| = 0 (1)$$

Weighting factors are considered to be equal to 1: final electric energy balances have been assessed.

Under this hypothesis, the EnergyFlexHouse is a Net Zero Energy Building as clearly stated in figure 1: the overall use of electric energy accounts for 51 kWh/m^2 year, while the generation is equal to 53 kWh/m^2 year

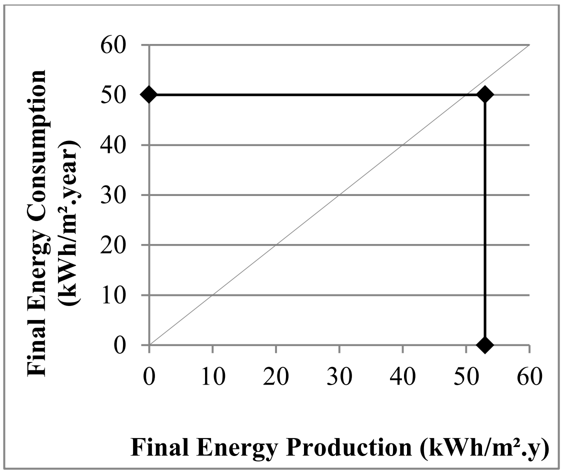

Figure 1 Net ZEB balance for the EnergyFlexHouse case study

Figure 2 shows the overall final energy consumptions for the original case study. The overall heating and cooling consumptions account for 4 and 2 kWh/m^2 year respectively. The assessed thermal loads for the whole year are around 20 kWh/(m^2 y).

The highest contribution to overall energy consumptions is due to the interior equipment use. The low building consumptions can be easily explained by a Givoni comfort zone analysis of the free-floating building.

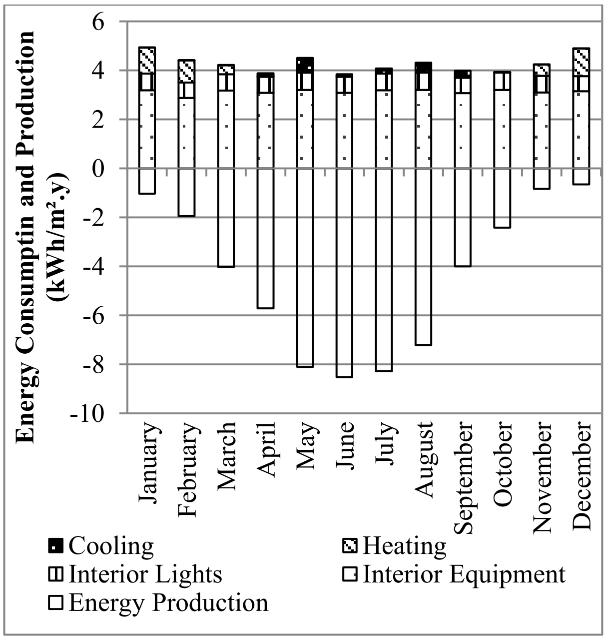

Figure 2 Split final energy consumption for the original case-study

In order to achieve better clarity only a fraction of the points contained in one year have been examined in figure 3. The darker points are connected to the outside conditions, while the others represent the indoor conditions. The points inside the smaller pentagon that is drafted between 18 and 27 degrees represent the comfort zone for still internal air. The larger pentagon, that develops from 20 to 32 degrees °C, represents the comfort zone for 1 m/s air.

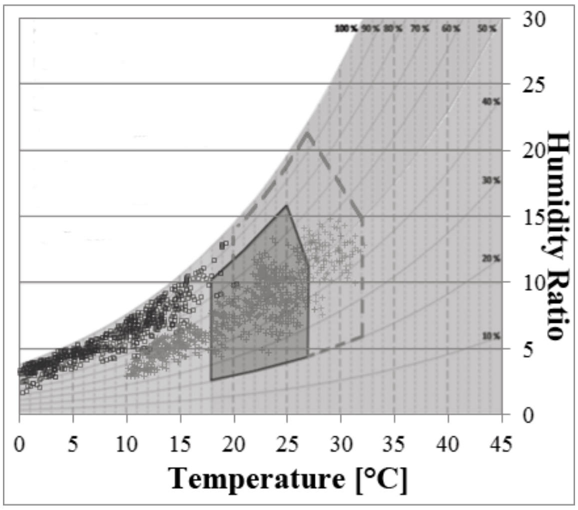

Figure 3 Givoni comfort zone analysis for the original building in Denmark

The external environment points are mostly comprised in the discomfort zone, while the inner building conditions are described in the following table (tab.2).

Table 2
Comfort analysis' results for the original case-study in Denmark

Comfort hours (0 m/s)	47%
Comfort hours (1 m/s)	56%

For still air the 47 % of hours in a year do not need heating or cooling. The situation does not get much better if the air speed rises to 1 m/s (56%) as a large part of the discomfort hours is caused by very low temperature.

The next sections will describe the proposed method's results for both the Denmark case and the La-Reunion one.

RESULTS AND DISCUSSION

Assessing the importance of solution sets in the original building

The following solutions were analysed:

1. ventilation
2. insulation
3. thermal mass
4. size of the south oriented window.

Each step was assessed with a separate simulation, results were recorded and compared. The ventilation (1) was set to a value close to zero on all the hours of the day during the whole year, the insulation (2) was reduced (U value of the insulation layers was reduced by a half). Moreover, a new composition of the envelope (3), much more massive and with lower insulation, was tested in the Danish climate. This envelope is typical of the tropical climates and is currently used in the ENERPOS building (Garde et al. 2011). The last scenario (4) simulates a larger (+50%) window in the south façade.

Fig.4 shows the overall thermal ideal loads calculated for the base case and for the four different scenarios. The most impacting is the insulation. Whether it is reduced or substituted by massive layers, the result is a very large increase in heating loads. A typical tropical massive envelope used in the Danish climate, in fact, causes a larger overall heating consumptions increase. While it has certainly a high impact on buildings with extensively applied natural ventilation strategies, for the selected case-study ventilation was not the most important solution chosen, and therefore its incidence on the loads is low. It must be noted anyway that the results are consistent with the physics of the problem: a building not ventilated, with large windows, occupants and internal loads would definitely tend to much higher cooling loads and smaller heating ones. The last solution examined, a larger window on the south façade has a low impact on the results, showing a small rise in cooling consumptions and a lowering of the heating needs.

Figure 5 shows, instead, the number of comfort hours for the scenarios calculated in free-floating mode, being consistent with the results of fig.4.

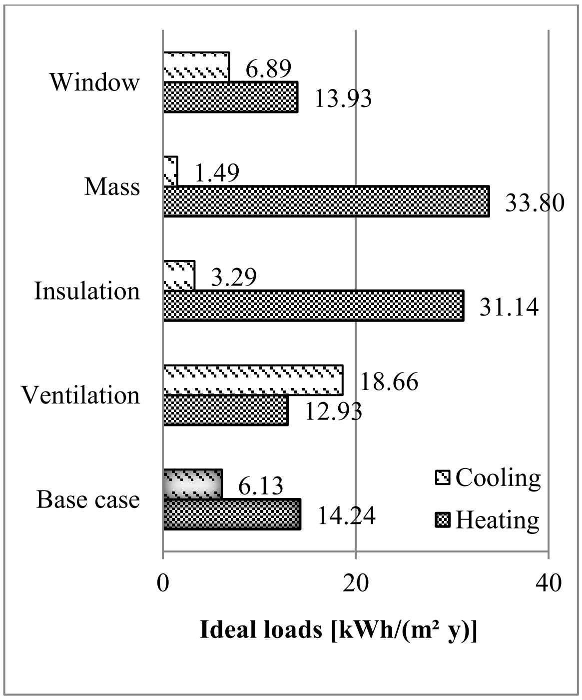

Figure 4 Ideal loads for the examined solutions in Denmark

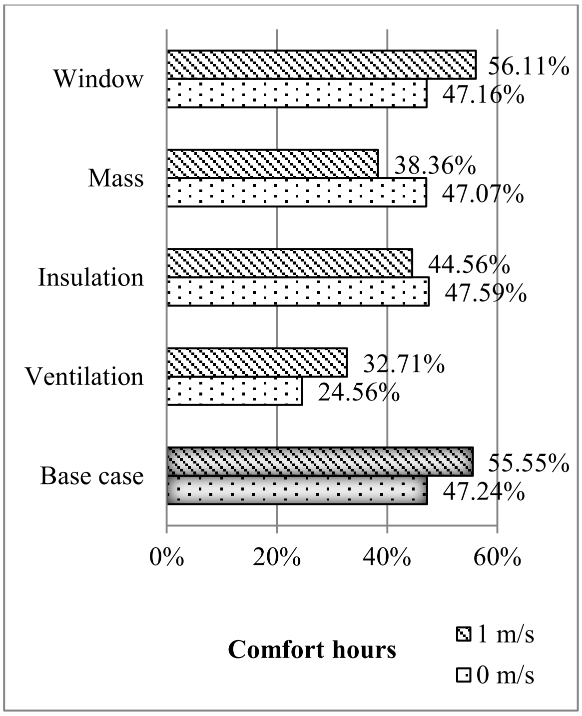

Figure 5 Givoni comfort zone analysis – hours of comfort per scenario in Denmark

Some apparently contradictory results between the two selected air speeds can be easily explained with the temperature and humidity comfort boundary values set up in the analysis and with the nature of the scenarios.
Switching to 1 m/s means that some point that were comfortable before, between 18 and 20 °C now are outside the Givoni comfort zone. At the same way it means that many points that with the previous configuration were outside of the comfort zone because the upper temperature setup was 26, now may be included. The ventilation scenario is characterized by severe overheating in a large part of the simulated year, therefore switching to a higher air speed has positive results on the number of comfort hours. Vice versa, the thermal mass and insulation scenarios, causing largely increased heating ideal loads, move the hourly points population on the left of the Givoni zone, as result of a severe overcooling. For this reason, when switching to higher air speeds the percentage of the comfort hours must inevitably be lower.

Moving to La Réunion

The building has now been moved to La Réunion, as it was built in Denmark, and simulated again.
Figure 6 shows the main results of the original Danish case study, simulated in La-Reunion.

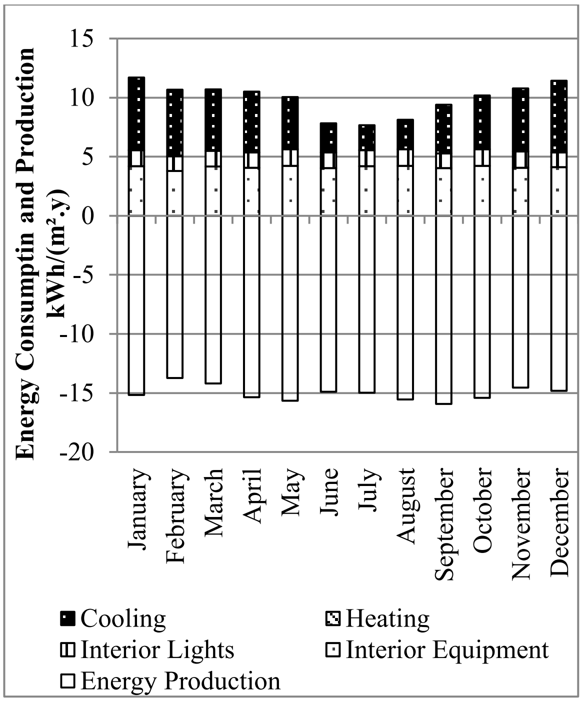

Figure 6 Electrical energy consumption and production for La Reunion, base case

The buildings' overall consumptions are around 59 kWh /m^2 y, and, at a first sight, the EnergyFlexHouse might actually seem a Net ZEB in terms of final energy also in La Reunion.
A more in-depth analysis leads, however, to understand that thermal loads equal to 94 kWh/(m^2 y) cannot be acceptable in a Net ZEB, and the only reason for the building to actually be able to reach the Net ZEB balance is a much oversized PV plant (Electricity production is around 90 kWh/(m^2 y))for the selected location. It has been verified that the building will reach the Net ZEB target easily in the new climate, because the generation system is largely oversized. As the aim of the paper is not the optimal sizing of the PV system but the assessment of the incidence of climate in optimal design, from now on the perspective will be focused on ideal loads and comfort analysis, to optimize the load side.
The comfort analysis for the original case study moved to La Réunion shows a very low percentage of comfort hours in the 0 m/s situation and an increase when switching to 1 m/s. This is a reasonable result as the majority of discomfort conditions hours is connected to overheating issues, as figure 6 suggests.

Table 3
Comfort analysis' results for the original case-study in La Réunion

Comfort hours (0 m/s)	3%
Comfort hours (1 m/s)	25%

In figure 7, the main solutions' impact will be analysed and in figure 8 the comfort analysis is shown. In a first step the original building will be modified, one solution at a time. In a second one, the best solutions will be assembled in order to obtain the final redesigned Net ZEB.
Some controversial results are shown in the figures but a reasonable explanation to them will be described in the following.

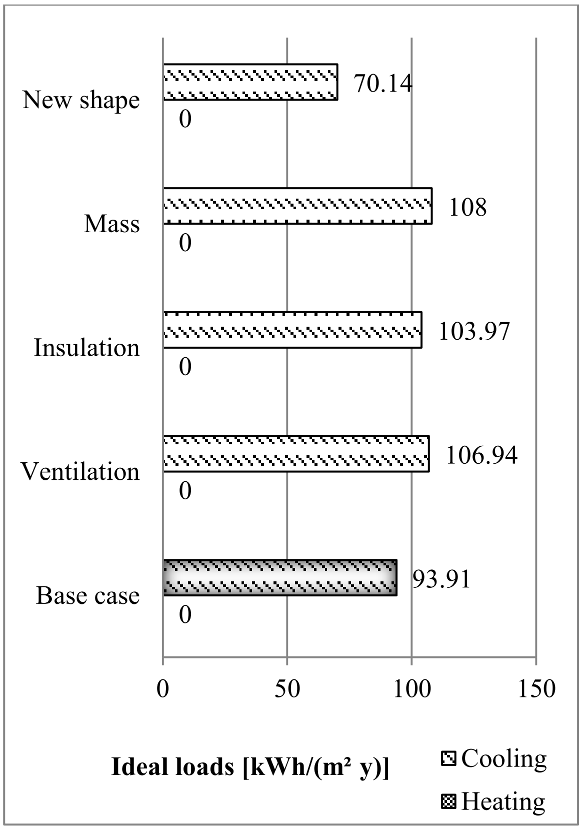

Figure 7 Ideal loads for the solutions examined in La Réunion

The new scenarios analysed for La Réunion are:

1. New shape,
2. Mass,
3. Insulation
4. Ventilation.

The 'new shape' (1) simulation includes a less tilted roof (around 20°) , a higher porosity of all the façades (around 25%), the substitution of all the triple glazing with single ones and a wide use of fixed sun shadings. Mass (2) and insulation (3) scenarios are the same that were used in the Danish case, while the ventilation scenario (4) uses 3ACH for every thermal zone.
The simulations were run with operating parameters (namely temperature set points) that were the standard for Denmark.
In La Réunion, buildings are commonly naturally ventilated, with large numbers of air changes per hour (Garde et al. 2012), using ceiling fans in order to obtain higher indoor air speeds, but with higher cooling set points (around 30°C, even 32°C in some cases).

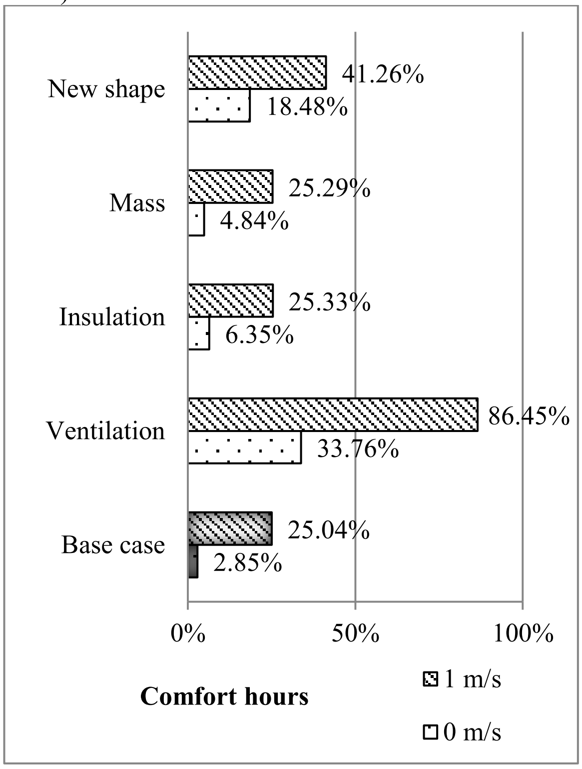

Figure 8 Givoni comfort zone analysis – hours of comfort per scenario in La Reunion

These design choices are mainly due to the adaptive perception of comfort of the native climate and to a shifting of the Givoni comfort zone borders because of the dependency on the indoor air speed. This allows temperatures that are commonly higher than 26°C, to be perceived as comfortable by the occupants. Therefore, when assessing ideal loads with a Danish typical setup, these considerations result in high cooling loads.
This point can explain why, even though natural ventilation strategies are so widely used in tropical climates, natural ventilation results (fig.7) are not good, resulting in high cooling loads. The insulation scenario shows that the percentage of comfort hours is higher than the base case but the overall cooling load is higher, even though the magnitude of this difference is not large: insulation is not a core solution in tropical climates.
The 'mass' scenario shows a higher percentage of comfort hours than the base case and a lower cooling consumption. In addition, these results do not show a large difference from the base case, but they are certainly affected by a higher uncertainty: thermal storages in buildings are deeply affected by ventilation, and therefore using the Danish low ventilation rates is a factor that may influence these results.
As expected the new shape scenario shows some higher improvements, but the most impacting data come from the ventilation scenario: a low increase of air changes causes a major variation of the results.

Choosing the use of air speed of 1 m/s (Ceiling fans) and higher temperature set-points (moving to the higher temperatures 1 m/s Givoni zone), the ideal loads are reduced and so is the need to use HVAC systems.

The final redesigned building will comprise the new shape, the thermal mass addition and the elimination of insulation in the walls and will be evaluated using a typical La Réunion cooling temperature set-point (30°C). The most important solution for La Reunion proves to be the natural ventilation that has been set to 10 ACH .

The final redesigned building cooling ideal loads are equal to 6.5 kWh /(m^2 y), with a reduction of more than 85 kWh /(m^2 y). Table 4 shows instead the results of the comfort analysis for the final building. The building is passively conditioned during more than a half of the hours. With a massive use of ceiling fans, more than 90% of comfort hours during the whole year would be guaranteed at 1 m/s air speed.

Table 4
Comfort analysis' results for the redesigned case-study in La Réunion

Comfort hours (0 m/s)	53%
Comfort hours (1 m/s)	92%

CONCLUSIONS

The study has described a methodology that aims to assess the most important features and solution sets useful in overcoming the challenges a building must face in its site. Each solution set needs to be analysed and its importance on the thermal performances of the building assessed by running parametric analysis and comparing results with the base simulation case. The proposed methodology may be used in the first design phases, in order to gain a preliminary understanding of the building performances in connection to the climate and to sketch the design as consequence. The bioclimatic approach has been described in connection to the Net ZEB framework, adding therefore the need to maximize the energy generation as well as optimizing the design in connection to the climate. The EnergyFlexHouse case study has been analysed in its original context, the main solution sets described and their incidence on the thermal loads assessed. The simulation of the original case study has been repeated in the new site, while new possible solutions were investigated, in order to achieve higher thermo-physical performances of the redesigned building, up to a 'best case' including the most impacting solutions examined in La Réunion.

The proposed methodology has many strong points: simplicity, capability of combining comfort and thermal loads approach and a design method connected to the bio-climatic conditions of the site. The main weakness is again its simplicity: some phenomena cannot be investigated with the due level of detail but just with a preliminary design level of depth. The proposed methodology has proven able to identify the following results. In the colder Danish climate, the most impacting solution sets for the building are:

- very low U value insulation,
- as low as possible ventilation rates in winter while answering in any case the comfort needs for the occupants,
- fine tuning of the natural ventilation strategies in summer, in order to lower the cooling loads.

For the La Réunion case study the best solution set includes:

- less compact shape of the building, higher façade porosity to maximize natural ventilation and wide use of solar shadings to minimize the resulting solar gains,
- massive use of natural ventilation strategies,
- use of ceiling fans.

The major outline of the work, however, is connected to the proposed methodology, that has proven able to assess the most effective solutions for different climates: a Net ZEB is not a solution set able to perform at its best in every climate condition. A 'design with climate' approach is therefore needed in order to develop the best solution to improve the performances of the building.

The best approach is to maximize passive techniques and therefore to minimize energy consumptions and environmental impacts during the operational phase, and on a life cycle approach, of the overall embodied energy required (when HVAC systems need to be installed).

A Net ZEB designer cannot disregard these aspects, as a Net ZEB balance is not merely an algebraic operation, and must take in consideration the energy efficiency of the single components and of the overall system involved.

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