INTERDISCIPLINARY DESIGN FOR THE DEVELOPMENT OF A WOOD HOUSE WITH POSITIVE ENERGY

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ABSTRACT: We present the work done for the wood prefabricated house Napevomo, a prototype of high energetic performance for the international competition Solar Decathlon Europe (SDE) 2010. The house is the result of the collaboration between an architect (Chilean), a designer, 25 companies from the Aquitaine region (France), 12 engineer students from the Arts et Métiers ParisTech (Bordeaux), and professionals from the Center of Technologic Innovation (CRT) Nobatek.

The main axis that guided the collaborative work of Napevomo were: energy performance, user comfort, wellbeing, respect for the environment and innovation. This axis were put together through the architectonic shape in which environmental conditions and new technologies gave visible, sensible and functional characteristics to the house.

KEYWORDS: Laminated Green Timber, House with positive energy, bioclimatic architecture

1 INTRODUCTION

The Napevomo house (Figure 1) links technologies and innovations to improve the energy design of residential space and it encourages the responsible use of natural resources. This is possible through the participation of Napevomo in SDE, which becomes a laboratory for testing new technologies and ideas coming from the academia and industries. Made of natural materials, Napevomo is designed to have a limited environmental impact while offering its inhabitants a high quality comfort.

From a bioclimatic point of view a vegetal roof is auto irrigated to cool its façade. At the same time the house has an irrigation system which reuse grey waters and recover rainwater for the vegetal roof and the east façade (also vegetal) irrigation. Worms are used for greywater purification

From a point of view of technical development, the house used green glued wood of maritime pine to make glulam (10,6 m) and curved glulam. An air cooling system based on phase change materials (PCM), more specifically paraffin, is used to maintain thermal comfort during summer,. Electricity and hot water are both generated through a solar cylinder parabolic collector able to track the solar trajectory [1].

Figure 1: Napevomo house on site

Napevomo house participated in the first Solar Decathlon Europe, in June 2010 in Madrid, and won the first prize in sustainability criteria. Napevomo means "Do you feel well?" in the Cheyenne language, and it represents the

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design concept behind this modular solar house, as a tribute to the deep respect that native Americans devoted to nature.

Solar Decathlon [2] is an international competition open to universities and organized by the American Department of Energy. Since the first edition in 2002, it is held every two years in Washington. Every team aims to design, build and use a solar house with a positive energy balance. On 2010, for the first time the Polytechnic University of Madrid with the Spanish Ministry of Housing has proposed a European edition. This first edition took place in June 2010 and welcomed about 190,000 visitors, alongside the Manzanares River. This event gathered seventeen student teams from all around the world (United-States, Germany, China, Spain, Finland, and France). It is characterized for employing a rigorous point system to assess the environmental features of each prototype house, described in detail in Figure 2.

The origins of Napevomo project were set in October 2008, when a group of engineering students of Arts et Métiers ParisTech in Bordeaux decided to participate in Solar Decathlon Europe 2010. Quickly, the team was built with the support of the Arts et Métiers ParisTech school and a couple of professors from the campus of Bordeaux. The main objective of those early sessions was to invent and build a sustainable solar house. A year later, a whole organization was set around the project, which has considerably expanded throughout its ambitions. Napevomo is an innovative demonstration project around energy efficiency in buildings in Aquitaine, involving numerous regional, national and international partners. The project team gathers companies, higher education and research institutions for the development, building and monitoring of the solar house prototype Napevomo.

### Figure 2: Solar Decathlon 2010 criteria

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### 2 DESIGN CONCEPT

#### 2.1 FORM GENERATION

First ideas around the prototype started with a dialogue within the project team. Each student described their ideas with general concepts, such as connection to nature, transparency, fluidity, or natural shapes. Combined with other requirements like local identity or low environmental impacts, the architect translated these words into conceptual shapes (see Figure 7).
From those early sketches, a curve shape that slightly touched the ground can be perceived. Those shapes were inspired from a water drop. Finally, the curve evolved towards a shape that was evoking a leaf, lying on the ground. At that time, the Napevomo concept was born.

Also, architectural detailing would take into consideration passive and active interactions between Napevomo and the sun. Bioclimatic architecture is a way of building an identity around a coherent concept [3]. Like conventional solar passive house, the aim was to protect the house from solar radiation in summer and capture heat and light in winter. However, as for many passive solar houses, roof pitch is often dictated by the optimal angle with the sun, giving for example houses with highly pitched roves in the North, and rather flat roves in the South (Figure 8). Thus, integration of solar technologies often brings architectural constraints that reduce creativity. From these considerations the project team approached an industrialist who was developing a solar concentrator that would be adapted to the building. Apart from technical interests in this micro Concentration Solar Power generator, this particular solar panel was not depending on the roof pitch. Indeed, this solar system is tracking the sun, thus reaching highest performances at any time. The following challenge was to integrate this system while preserving the architectural concept.

As a result, the curved roof appeared as a response to the curved floor. This curved roof can be seen as a well-balanced wave, which welcomes a technical element on the north side, and captures light and sun for living areas on the south side. This wave is the mark left by the sun on the house (Figure 9).

The team chose to integrate technological elements as a part of the architecture, as current Building Integrated Photovoltaics do (BIPV) [4]. In the end, the design process followed one principle: technologies do not have to be added once architecture is designed. On the contrary, they must be considered as proper architectonic elements that contribute to the overall concept. The successful integration of technologies was achieved with a strong collaboration between the architect and the engineering students, into to take all technical constraints at the first stage of design process and preserve the technological performance. In other words, technology was employed as a material that can be worked like others.

2.1 BUILDING PERFORMANCE

The building’s envelop was designed to minimize heating and cooling energy needs. The team selected insulation materials which are, or could be produced in the region, to avoid further fuel consumption and greenhouse gases (GHG) emissions due to transportation. Cellulose wadding in the roof and the floor was supplied by a manufacturer recently settled in the region. Wood fiber boards for the walls were imported from the Swiss forests, but could potentially be sourced from the Landes forest (closest forest from the construction site) in the future. Those materials have other environmental benefits such as being made out of waste or by-products. Technically, wood fiber boards are suitable for external insulation, which limits thermal bridging. Cellulose wadding and
wood fiber also bring more thermal mass, compared to conventional insulation materials [5] (Figure 10 and 11).

For the project, the use of maritime pine has an important meaning. First, it demonstrates the mechanical properties of this species, which are more than acceptable for construction, when timber is processed to make glulam beams. Moreover, the glulam beams used for Napevomo are produced using an innovative process, especially developed by the research project ABOVE. That project aimed to develop an industrial process which green timber is glued and laminated, before drying it out. This method is not only bringing stronger properties to the beam than conventional glulam beams, but it also allows saving energy since woods parts which unfit for construction like knots are removed before the drying process. The availability of this technology was a great argument in favor of timber. Thus, the team decided to develop a house that would tend to be 100% from maritime pine, in order to support the development of local activities around timber construction in the region. Furthermore, Nepevomo’s curves would be challenging for this emerging technology (Figure 12 and 13).

Then, along with building architecture, architects and engineers incorporated heating, cooling and ventilation strategies to reduce energy consumption. Heating Ventilation and Air Conditioning (HVAC) facilities have a crucial rule to provide the required comfort level by making the best use of the produced energy [7]. The
building management strategy was based on two simple principles: the first one is that solar thermal technologies are, by nature, more energy efficient than photovoltaic technologies, which have a maximum yield of 20%. The second principle is that simplicity and compactness of systems often lead to energy efficiency. Early in the design process, these two principles guided the team to determine its strategy to heat the house using solar collector for domestic hot water. Moreover, Incoming fresh air would be warmed through heating modules, which are supplied by solar hot water. The aim of this approach was to minimize the use of electricity as possible (Figure 15).

![Figure 15: Heating and cooling energy needs for Madrid](image1)

Passive cooling strategies were also envisaged first to reduce electric consumption. The first option was to store heat in mass, using thermal capacity of materials such as earth, sand or water. The second option is to use latent heat of fusion or evaporation. Thus, floor and walls were covered with dense materials such as earth tiles. Secondly, latent heat of fusion of phase change materials (PCM) were used to cool the air via a heat exchanger in summer. Finally, self-irrigated green roof would evaporate rain and treated grey water in order to minimize solar gain in summer. Natural cross-ventilation was also a solution for mid-season and night cooling, therefore operable windows were designed on each facade of the house. To complement passive solutions, a heat pump were also installed to control thermal comfort in the house throughout the air system (Figure 16).

![Figure 16: Air heating and cooling active systems](image2)

### 2.1 ENERGY GENERATION

The objective for the solar technologies was to produce enough energy to make the house self-sufficient, out of a restricted area. Thus, the team had to find a trade-off between architecture and engineering criteria in order to find a solution which integrates a maximum of solar cells while respecting aesthetics and architectonic concepts. A good compromise was found with a parabolic through concentrator that a local company wanted to test on buildings. The idea was to generate both hot water and electricity with a combined solar concentrator. In this system, direct solar radiation is concentrated via a parabolic through mirror towards high performance PV cells (yield of about 20%) (Figure 17). To preserve this yield, the cells have to be cooled with water. As a result the team obtained hot water suitable for domestic and heating use. This system presents numerous advantages. Firstly, it saves area for a green roof because additional solar collectors were not needed for hot water. Secondly, it uses less silicon cells than conventional PV panels for approximately the same daily production (Figure 18). Therefore energy and investment pay-back time is reduced. Finally, energy production in early and late hours must be higher than with fixed panels.

![Figure 17: Parabolic PV system](image3)

![Figure 18: Water system](image4)

Low energy consumption houses consume very little energy during its use phase. By contrast, the energy needed to manufacture the construction materials, transportation and demolition of the house components represents an important part of the overall energy consumption over its life span. Beyond energy sobriety (reduction of energy consumption) and use of renewable energy, Napevomo was concerned in reducing the building environmental impact. Thus, Napevomo was thought to be environmentally friendly all over its life cycle (Figure 19). Indeed, technical choices had been made by referring to life cycle assessment studies on materials to be used.

![Figure 19: Building total embodied energy](image5)

Consequently, the house has a low impact concerning GHG emissions, energy balance, water consumption, etc (Figure 20). For example, the timber structure is 100% made of maritime pine, which is the most abundant wood in the region of Aquitaine Landes Forest.
Finally, while life cycle assessment and bioclimatic architecture allowed to reduce environmental impacts of the prototype, the team wanted to highlight important concepts of sustainability. The design of a sustainable building changes the way we live in the world. A bearable way of inhabiting the world could be to try to make human activities comparable to an ecosystem, where matter and energy flows are renewable, reused and recycled. In an ecosystem, waste from a species is a resource for another one. This approach led to consider energy, water and waste management, materials and construction techniques through adapted tools and methods. First, choosing efficient appliances and various accessories (i.e. check valve, water saver) to reduce the consumption of drinking water to the house. But in addition, reducing the consumption of drinking water, the team founded it necessary to reuse the maximum wastewater produced for applications such as irrigation or sanitary usage. Wastewater is then collected and recycled through various stages of filtration based on natural processes of decomposition of organic matter.

3 BIOCLIMATIC CONCEPT

The design of the orientation and size of windows of the house was calculated optimizing the amount of solar light during all seasons of the year. The goal was cumulating heat from the weak solar radiation in winter and to protect the house from the great solar radiation in summer to keep it fresh inside. Interior heavy floor of ceramic tiles were incorporated as thermic mass in the house to reinforce the accumulation of heat by solar radiation in winter. Windows on each facade and a skylight on the roof guaranty a level of natural light enough to have homogeneity at the interior (Figure 21 and 22). There is no need of artificial light during day time.

Its bioclimatic architecture is the first element of this concept with:

- **Openings optimally designed to use sun’s heat and light**: large openings on the south facade for important heat gains, zenithal window that lets a significant amount of light to enter.
- **Self-irrigated green wall and roof** that helps natural cooling of the house, thus providing a good comfort during summer. Irrigation water will come from rainwater collection and natural recycling of wastewater (with a lombric-based filtering process).

Other important elements are part of the natural spirit of Napevomo:

- **Choice of a carbon neutral construction material**: Maritime Pine from the Landes forest, in the South-West of France. A **new technique of timber lenghtening**, the ABOVE process, uses green wood. It reduces energy consumption usually required for drying while providing high resistance glulam beams.
- **Waste upgrading** thanks to the use of low process insulation materials such as wood fibre and cellulose wadding.
- **Natural furnishing elements**, like **raw clay tiles** in floor and wall elements, which also reinforce thermal comfort.

All the above design strategies and technologies, allowed to achieve a high level of indoor comfort levels across the whole year. A TEHOR® sensors [8] was positioned 2.4 meters above floor level in the living room to measure the ambiance (occupation, temperature, natural and artificial lighting). Napevomo house was monitored from: January 1st 2012 to April 15th 2013. Exterior temperature was measured by a weather station. During this period, Napevomo was used as a lunch room by the employees of the campus. Thus, this occupation was different from what it was designed for.

Figure 19 shows the illuminance measured by the TEHOR sensor as a function of time. During summer, the illuminance is around 1000 lux (diffuse light) at the maximum of the day while it can reach 3000 lux (direct light) in winter. This daylight variation shows the impact...
of the overhang on light diffusion in the living. Finally, figure 23 shows that openings ensure an adequate light for a living space.

Figure 23: Daylight illuminance in Napevomo from January 7th, 2012 to April 15th 2013

Thermal comfort is assessed by plotting indoor air temperature vs. the weighted mean exterior temperature on seven days $T_{\text{rm}}$ as define in the European standard EN 15251 (see Figure 24). Only the temperature during opening hours (9:00 to 18:00) is drawn. Thermal comfort limits defined by the same standard are also presented in the same figure. The figure shows first that indoor air is cooler than should be expected. However it may be explained by the low occupation rate (few space heating and low internal gain).

On the other hand, Napevomo house has a good thermal behaviour when there is not space cooling systems functioning since there is not overheating in summer. Furthermore, there is overheating during mid-season (exterior temperature between 5 and 12°C). This thermal behaviour demonstrates that the combination of the overhang and the south-facing bay window is well designed and ensure its bioclimatic function.

Figure 24: Indoor air temperature vs. weighted 7-day mean exterior temperature in 2012 (light green) and from January 1st 2013 to April 15th 2013 (dark green): Thermal category B comfort limits for a building without a cooling system functioning (solid lines) B and for a building with a heating system functioning (dashed lines)

Napevomo was conceived with regard to the major principles of bioclimatic architecture. During the winter, it captures, stores and conserves the heat, while during the summer, it protects from the sun and dissipates the heat. The team translated those general principles into specific criteria as follows:

- **Compactness**: Napevomo has a shape factor near to one, thus with the minimum of exterior surfaces.
- **Distribution of windows**: the windows are mainly located on the south side to capture maximum sunlight in the winter. Openings are minimized on the east and especially on the west sides, because the solar gains are very important on these fronts in the summer. On the north side, which receives no solar gain in winter, glass surface is minimized.
- **Arrangement of spaces**: the spaces are arranged according to the path of the sun. The living space is wide open on the south, while buffer areas (toilet, bathroom, mechanical room, kitchen) are located alongside the north façade.
- **Sun protections**: Napevomo features two type of solar protections: the first one is a sunshade overhang which protects the south facade (90 % all summer). Shutters complement sun protection on the south side, as well as for windows of the other facades.

### 3.1 INNOVATIVE TECHNOLOGY

The Napevomo project highlights many high techs with:

- The use of **phase change materials**, to store heat during the day and release it during the cool night. It reduces heat peaks and reinforces summer comfort. It is coupled with a ventilation system that makes heat transfer easier and optimizes energy performances (Figure 25).
- Solar energy production is optimized via an innovative **hybrid collector**: a parabolic-through concentrator. This micro-CHP system simultaneously produces electricity and hot water, which is not only used for domestic needs but also for space heating in winter. Thus Napevomo can totally works from solar energy.

Figure 25: Phase Change Material

### 4 A TRANSPORTABLE HOUSE THAT CAN BE DISASSEMBLE

Because of the needs of the competition in Madrid, the house has been constructed in the Aquitaine region and transported on a truck in multiple parts in order to be assemble, disassemble and reassemble at the University of Talence in France (Figure 26 and 27). Although Napevomo’s technology is complex and sophisticated, the house offers to its users a real living comfort thanks to an easy management. It is made possible through a building automation control system that centralizes all comfort parameters. For example, lightings and shutters controls can be entirely automated. For artificial lighting Napevomo uses LED technology. They have two advantages: they consume only 1-3 Watts, while common...
Lights consume 50 to 60 Watts. Their lifetime can reach 100,000 hours (more than 50 years for an average use of four hours per day). LEDs are cheap, environment-friendly and totally safe for human health.

What is particularly relevant for this project, it is the low carbon emissions produced during its construction and assembling phase, thanks to its prefabricated modular building systems (Figure 28).

4.1 ENVELOPE STRUCTURE

Napevomo envelope is comprised of 2-dimensional modules designed to be portable and enable rapid assembly of the house. Therefore the house is decomposed into four modules cover four walls and four floor modules.

To achieve an adequate insulation to fulfill the SDE demands, the different modules consist of a frame of local wood (Aquitaine) and have been transformed and glued green without drying.

Thermal insulation panels used comprises natural wood fibers and cellulose. In the design and insulation panels placed special care in order to minimize thermal bridges in the envelope. Moreover, the thermal resistance and the phase shift that allows the combination of components used in the facade. This also brings to the interior comfort of home incorporating mass inside the house that can accumulate and restore heat passively.

4.2 MODULARITY

The constructive system was conceived to be prefabricated and easily transportable, while ensuring high energy performance. The modular design of the architectural structure of the house allows the transport mounted and multiple dismounted of the house with the purpose to place it in different spaces. This modularity also allows testing the System of quickly assembled based on 2 dimensional modules (walls and floor panels and cover).

For the structure of the walls, the team opted for a skeleton structure. This technique allowed the realization of a resistant structure with the use of little sections (120 mm x 45 mm), and is suitable for prefabrication. The floor and the roof are formed of boxes structured by glulam and filled with insulating material (Figure 29).

5 OUTCOMES

Napevomo ended the competition at the seventh place and won 5 prices amongst the 10 contests:

- 1st Price of Sutainability
- 2nd Price of Engineering and Construction
- 2nd Price of Comfort conditions
- 2nd Price of Innovation
- 3rd Price of Solar Systems

The other contests were:

- Architecture
- Energy balance
- Appliances
- Communication and social awareness
- Industrialization and market viability

6 CONCLUSIONS

Napevomo house corresponds to the experimentation of various technologies through a house since its material
can be adapted to accommodate voluminous technical elements. It can demonstrate flexibility in use which allows the wood also to provide a great range of possibilities.

Most of the project’s lessons and approaches had been continuously revisited in different academic assignments, particularly the “Casa Solidaria” initiative at PUC School of Civil Construction, which was designed to participate in Solar Decathlon Latin America y el Caribe 2015 (SDLAC2015) Colombia (Figure 30).

Figure 30: Casa Solidiaria digital model.

On Casa Solidaria the use of timber is also widely recognizable, but integrated into a panel building system, able to be assemble onsite by unqualified workers. It indoor comfort parameters correspond to tropical climate, as it was designed to be assemble at Haiti, as a house for refugees from 2010 earthquake. It also integrates innovative approaches for HVAC, Bioclimatic design and integration of sustainable technologies with low-tech architecture.

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