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FROM MODULES TO COMMUNITIES: FOSTERING FLEXIBILITY AND AGGREGATION IN SCHOOL INFRASTRUCTURE FOR USTAINABLE SMART TERRITORIES

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Abstract. Developing smart cities implies developing networks with the territory: not only communication and data networks, but also service networks that avoid unsustainable depopulation or impoverishment of rural and peripheral territories. With this purpose, the outcome of a research on how to respond to the need for new school infrastructure in northern Argentina is presented. In this way, the school "network" can be sustainability-oriented and offer a certain level of education to the entire population, regardless of the location of residence. For this purpose, a prefabricated wooden module is proposed that is designed according to the very hot climatic conditions found in northern Argentina (bioenvironmental zone I according to IRAM 11603) and that can be the basic cell for the formation of new schools, buildings for public services and even residences or guest houses. The dimensions of the module and the stratigraphies and materials that make up the walls, floor and roof of the prefab are described. The various possibilities of aggregation and the HVAC system are also explained. The energy needs for the entire year are estimated, which, thanks to the installation of rooftop PV, can be fully met even when the location is "off grid," if adequate batteries are provided. Connected to the power grid, which can be used as a virtual accumulator, the module is still energy self-sufficient and therefore suitable for carbon-free operation.

Keywords: Wood Construction, Sustainability, Energy Efficiency.

Foreword

This paper aims to propose a contribution about the transition and integration of school infrastructure into the inclusive and sustainable system of smart cities. The results are the outcome of an inter-university research activity involving researchers

from UNNE Universidad Nacional del Nordeste (Chaco, ARG) and the Politecnico di Torino (Italy) about the response to the needs of new schools in the Argentine North.

First of all, underlying the research work is the distinction between 'smartization' and digitization: the latter must eventually be ancillary to the former, otherwise the goal of making stably diffuse, smart and sustainable the social, infrastructural and building system that constitutes the city would be missed, because it would be limited to management strategies (algorithms) that are often feedback-driven and that improve the contingency of the present i.e., the effects on the inhabitants, but do not govern the evolution of the city as an inhabited territory. The spin-off would thus be more about citizens than about the city, whereas this study is focused on the "physical" infrastructure represented by buildings.

The objectives of this study address the need for a more widespread and inclusive school infrastructure through the proposal of building modules for sustainable and energy efficient buildings.

Context

The reason why

Why this research? In a context of transition to smart cities, the deficit of classrooms in Argentina identified in the report *Infrastructura Escolar 2023-2033* by CAMARCO's Office of Studies [1] raises the need for new construction, but leaves the identification of typological modes and characters to local initiative. This may induce inertia and inefficiencies that result from the prototypical character of each construction site and may favor the choice of the big city for new settlements, due to better infrastructure and lower supply costs, exacerbating the imbalance between rural or peripheral areas and the city, contrary to SDGs Nos. 4 & 10 (Quality education & Reduce inequalities).

The Argentine government has developed several projects to improve school infrastructure and the quality of education in Chaco province, including through the *Plan Nacional de Infraestructura Educativa*. In recent years, a significant number of new school constructions and renovations have been completed, along with ongoing interventions throughout the country, with 27 projects already completed, 38 in execution, and another 120 funded in 2024 alone

These investments are part of a broader effort that includes logistical support, distribution of educational materials, and enhancement of essential services for schools in disadvantaged areas. You can find additional details on the official website of the Argentine government or in documentation published by the *Ministerio de Educación*.

Sustainable and smart

In this frame, a design proposal for a reversible (i.e., deconstructible) building system that has versatility of aggregation, flexibility of use and technological integration, and ease in adapting to environmental, even rural, contexts is designed. It allows to conjecture a built environment that itself behaves smartly, preventing depopulation of

rural and peripheral areas through the deployment of low-cost but not low-quality school infrastructure. The school very close to residences can contain costs to the State through metabolization of digital resources and network integration, this facilitating the daily presence or co-presence in teleducation. That reduces the resources used for faculty and pupil travel, thus the number of decentralized schools can be increased without disproportionately multiplying personnel costs. The idea is for aggregations, varying according to the context, of modular building units that can offer, depending on local needs, teaching units (classrooms), services (bathrooms, kitchen, school canteen etc.), guest quarters for teachers, social gathering and co-working spaces, etc., even growing or decreasing rapidly (dry construction with disassemblable prefabricated elements) according to changing needs, with a "smart" and self(?)-adaptive strategy.

A smart school can then provide for the digitization of the infrastructure and is not merely "digitizing" its students (e.g., equipping them with interconnected tools), but is organized for active sharing of networked teaching, where, for example, teleducation is bidirectional and not throttled by the limitations of a tablet screen. For this to happen the building must be sufficiently flexible, given that the lifespan of the building container is much longer than that of the network and the technical components that constitute its digitization, and maintenance and expansions of these services should be able to be carried out while containing interference with the activities taking place there.

Methodology

First of all, the researchers considered the situation of public school buildings in the different Argentine provinces (as described in institutional documentation available online) and identified the greatest building needs in relation to school-age population and lower average income in the northern provinces, which greatly limits the access to private schools. The provinces of Misiones, Chaco and Corrientes are among the poorest in Argentina, with high unemployment rates and low fiscal capacity. These provinces are often unable to finance school construction due to limited economic resources. According to a report by the *Ministerio de Educación de la Nación* (2021), schools in these regions suffer from a chronic lack of resources for construction, maintenance, and expansion of school buildings.

For this reason, Chaco, Corrientes and Misiones were selected as the setting for this study. Although the Argentine government has launched several construction and renovation programs to address the deficit of school buildings, the effectiveness of these programs has been limited by economic and administrative difficulties. The *Plan Nacional de Infraestructura Educativa* (PNIE), launched in 2016, included investment in the construction of new schools and renovation of existing ones, but according to the aforementioned report (*Ministerio de Educación*, 2021), the provinces of Misiones, Chaco, and Corrientes received only a fraction of the funds allocated to the wealthier provinces [2].

For the province of Chaco, Argentina, substantial investment in school construction has been undertaken, aimed at improving the quality and accessibility of educational facilities. The provincial government, in collaboration with national and international funds, has planned 180 school construction and renovation projects. This plan includes maintenance works for more than 1,200 schools, with special efforts in remote areas such as “El Impenetrable”. Some specific projects are supported by organizations such as FONPLATA, which has funded educational facilities to ensure an inclusive and safe educational environment for students with special needs.

In particular, the school in Fuerte Esperanza, for example, received funding for a new 230 million pesos’ facility, including classrooms, laboratories and specialized services for students with disabilities. Other interventions include building technical schools and improving infrastructure for rural schools through specific programs such as PROMER II [3], in partnership with UNICEF.

The research group then focused on climate and its relationship to building sustainability and resilience to climate change. The goal is to devise a module that can be as energy self-sufficient as possible by harnessing solar energy: e.g., the sunnier the day, the more energy is obtained for cooling needs, with a self-adaptive effect with respect to heat waves, considering the daytime use of the school. To evaluate this behavior, an energy simulation software (compliant with ISO 52016-1:2017 and ISO 52022-1:2017) was used to compare the photovoltaic production feeding a heat pump system with the needs for seasonal air conditioning, adopting climate and irradiance data from Resistencia (Chaco). The building envelope was characterized through its transimittance and thermal wave phase shift and attenuation (the latter only for opaque parts). All envelope calculations were performed in accordance with the standards ISO 6946:2017 and ISO 13786:2017.

Results

First, the module has been conceptualized and designed by reflecting on Matías Taborda, Gerardo Esteche and Carlos Marcial’s design for the Tamandua school in Misiones [4]. This research’s architectural result can meet almost any school building requirement with several prefabricated modules joined together. For example, the CAMARCO report for the period 2021-2033 estimates the full-time elementary school building demand in Chaco, Misiones and Corrientes as follows: 139 new schools in Chaco (corresponding to 834 classrooms), 129 new schools (772 classrooms) for Corrientes Province, and 148 new schools (889 classrooms) for Misiones Province. Even conjecturing that full-time is not extensively adopted (halving the need for space because each school can operate on two shifts) and that resources can be found to meet half of the demand that thus remains, building demand remains high with more than thirty new elementary school per Province (6 classrooms each), expected to be built at the rate of about 3 per year.

Each building can be organized through the replication of the prefabricated module in multiple floor plan configurations, all with a single floor elevated from the ground (with an accessible cavity, good to protect the building from flooding and soil moisture) so

as to promote accessibility and safety of displacement. The adoption of large openable transparent surfaces increases natural light and the relationship with the surrounding environment (each room accesses the outside) that are stimulating learning, as indicated, e.g., by the studies of Peter Barrett et al. [5].

Sustainable goals

The purposes are the containment of construction costs and time combined together with SDG No. 4 “Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all”: the choice of a prefabricated wooden module with the same structure for different uses in fact allows to control production costs (thanks to industrial replication of identical units) and to ensure the same level of construction quality in each school building, regardless of its location.

The design phase reasoned about the entire lifespan of the building: management and maintenance costs are reduced because the module lends itself to different destinations, interior distributions and furnishings, as well as the possibility of being aggregated in multiple configurations and, at the end of its service life, disassembled and reused. Moreover, the main wiring and piping run in the ceiling of the porch and are therefore serviceable, reconfigurable and expandable while working without interfering with classrooms. The air conditioning system is suspended from the underside of the module floor and therefore maintainable from the gap formed between the natural ground and the building floor. In addition, the possibility of equipping the roof with photovoltaic panels that power the electrical services and the heat pump air conditioning system makes the building almost self-sufficient.

Structure

The entire module, which measures 9 x 5 m in plan and has a usable internal area of 4.76 x 6.70 m, is built using prefabricated wooden elements.

The load-bearing structure consists of two vertical frames that support the lower floor and the roof, on which any partitions are anchored. On the decks are placed the side walls and those toward the loggias. The former consist of opaque wafer panels that can be omitted in the union between modules; the latter consist entirely of window and door frames, opaque only for the entrance door and for the upper part to close the different height of the envelope for the two glazed façades.

The large windows protected by the loggia roof-overhang allows a very favorable visual relationship with the outside and a high daylight factor with good control of direct solar radiation. The choice of glazing type (single or double, or triple glazing) can be reconsidered depending on climate and financial availability, so as to contain the resources allocated to the most expensive component of the vertical envelope.

Each module is composed of the elements and layers shown in the previous Table 1. All the components can be moved by a single medium-duty truck (US class 6).

Table 1. List of components of a prefabricated module

Material	Unit	Quantity	Thickness [mm]	Mass [kg]
Plasterboard	m^2	97.50	12.50	853
Wooden planking	m^2	207.53	20	2283
Aluminium roofing sheet	m^2	36.94	1	103
Waterproof PVC sheet	m^2	36.94	1	51
Vinyl flooring	m^2	36.76	5	221
Wood fiber panel	m^2	134.01	100	3015
Windows & entrance door	m^2	21.6	70	756
			Total	**7282**

Thermal specifications of the envelope

In the specific case (northern Argentina), a median solution was decided upon, with double normal glass and a wooden frame. The layers of the opaque parts, including floor and roof, are summarized in Table 2. Thermal transmittances are calculated according to ISO 6946:2017 [6]; thermal wave phase shift and attenuation are calculated according to ISO 13786:2017 [7].

In view of the current global climatic evolution, the research team decided to equip the modules with air-to-air cooling system, so as to improve indoor comfort even on days when the relative humidity and/or outdoor temperature do not allow for comfort conditions with cross ventilation alone, also in view of the foreseeable crowding of the rooms. The thermal insulation of the vertical opaque envelope, which might seem overabundant (K = 0.428 $W/m^2 \cdot K$ compared with the limit of 1 $W/m^2 \cdot K$ for level B compliance), is in fact aimed at containing heat re-entry in summer. Its periodic transmittance is 0. 265 $W/m^2 \cdot K$ and get a thermal wave attenuation of 0.631 and a phase shift of 6.258 h: in this way, the outdoor temperature peak reaches the classrooms when the evening hours allow a better performance of the cooling machine and, especially if classes are over, can be compensated with natural night ventilation.

The designed glazed envelope has an overall thermal transmittance K around 2 $W/m^2 \cdot K$, including the wooden frame, opaque and transparent parts. The latter are made with normal double glazing.

The roof was the subject of special consideration. It is designed with 10-cm thick wood wool thermal insulation and results in a thermal transmittance K of 0.409 $W/m^2 \cdot K$. The periodic transmittance is worth 0.248 $W/m^2 \cdot K$, the attenuation of the thermal wave is 0.614 and its time lag is 6.76 h, with thermal wave management similar to that of the

opaque wall. The K parameter is already thus half of the maximum allowed by the B level (0.83 W/m^2·K) of IRAM 11605, and in this way the effect of heat radiation from the ceiling is greatly reduced, benefiting summer comfort.

Table 2. Thermal transmittances and layers specs of the opaque envelope

Component	Thermal transmittance [W/m^2·K]	Layers (from inside to outside)	Thickness [mm]	Conductivity [W/m·K]
Floor	0.408	Vinyl flooring	5	0.17
		Wooden planking	20	0.14
		Wood fiber panel	100	0.056
		Wooden planking	20	0.14
		Wooden planking	20	0.14
Wall	0.428	Plasterboard	12.5	0.21
		Air gap	40	0.222
		Wood fiber panel	100	0.056
		Wooden covering	20	0.14
Roof	0.409	Plasterboard	12.5	0.21
		Air gap	100	0.625
		Wood fiber panel	100	0.056
		Wooden planking	20	0.14
		Waterproof PVC sheet	1	0.17
		Weakly ventilated air gap	30	-
		Aluminium multilayer roofing	3	160

In order to further improve indoor comfort, the thickness of the wood wool insulation layer of the roof can be increased to 18 cm: in this way the K is reduced to 0.258 W/m^2·K and the roof not only complies with Level A of IRAM 11605 for design temperatures down to -6°C, but also greatly improves summer behavior. In fact, with the 1.8-fold increase in thermal insulation thickness, periodic transmittance is reduced by 4 times (0.061 W/m^2·K), thermal wave attenuation by 2.5 times (0.238), and phase shift by 1.8 times (12.13 h: the thermal lag is directly proportional to insulation thickness). The improved behavior of the roof reduces the heat peak from the ceiling

by 1.6 times (according to the summer thermo-physical model with the heat-storage factors by the "Carrier-Pizzetti" method [8]). At 6 PM on a typical summer day, the heat arriving from the ceiling drops from 335 W to 206 W: these are not major numbers, but a significant reduction in radiation, and thus a consequent improved well-being for the occupants. The higher thermal resistance of the roof causes a negligible worsening of the overall summer behavior, due to the lower nighttime cooling by transmission: this is about 3 kWh/year, which is irrelevant anyway because it is provided by the photovoltaic system. In contrast, the winter situation, where PV may be less effective due to bad weather days, improves by 86 kWh, or about 14.9 percent.

HVAC needs

In estimating the winter needs, the presence of people was not taken into account: this is a conservative assessment, which allows the empty rooms to be prepared for the comfort temperature even on the coldest days and also allows the real electricity demand to be reduced, which benefits the behavior of the system on cloudy or rainy weather days. With similar caution, the prefabricated module, for the sake of safety, is considered fully exposed on all sides to the outdoor climate, even in the case of the summer power calculation in which, however, full room crowding was considered.

The thermal power required for each module is about 3 kW in winter and 4.3 kW in summer and is delivered by an air-to-air packaged conditioner, e.g., flat type, hanging from the soffit of the slab, in the cavity under the floor. Due to the conformation of the module, raised above the excavation of the foundations, the space is ventilated from multiple sides and accessible for maintenance (height of at least 1.5-1.6 m), and this placement keeps the system permanently shaded, with better efficiency due to the absence of overheating caused by solar radiation, and protects it from rain.

Eight photovoltaic panels with a total peak power of 3280 W are installed on the roof, which can be used off-grid with suitable batteries or connected to the power grid as virtual accumulator. In this way, each module is self-sufficient and carbon free throughout the year, as shown in Figure 1.

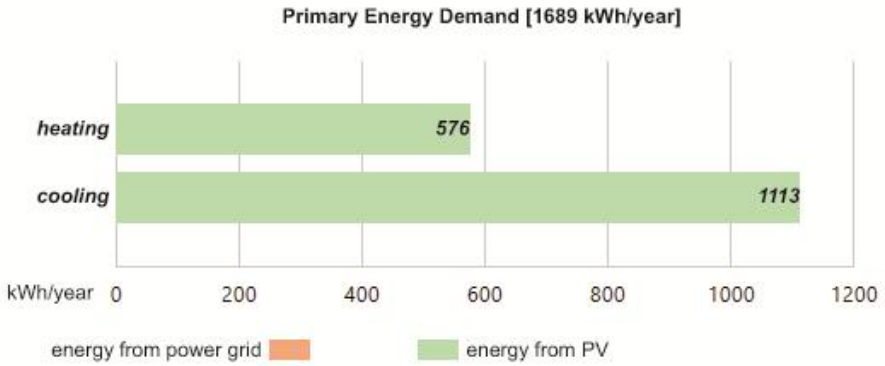


Fig. 1. Primary Energy Demand for a single module in Resistencia (Chaco) with 3,28 kW PV on the roof: no emission of Carbon dioxide all year round.

Discussion

The study of the prefabricated module resulted in maximum flexibility of use, with the possibility of aggregating and re-aggregating modules according to changes that may occur in their uses (Figure 2), and also of disassembling and reassembling them elsewhere if necessary.

The stratigraphies proposed in this study meet the Level B of IRAM 11605:1996 [9] for any outdoor temperature stipulated in the standard, for bioclimatic zones I “very hot” (and possibly II “hot”) according to IRAM 11603:2012 [10].



Fig. 2. 3D perspective views of possible aggregations of the proposed prefabricated module

The research team focused on adapting to the climatic context and meeting the demand for new schools with an easy, fast and reliable construction system to meet the requirements of quantity, quality and speed. The climatic data suggest the use of a floor plan organization with open connectives (e.g., porch or loggia corridors), which is beneficial for construction cost containment and natural cross ventilation of spaces, which, precisely because of the open distribution of porches, is effective and easily achieved in every room. The adoption of perimeter loggias, which echoes recurring construction patterns in Argentine rural schools up to the 1950s and in some of Soto

& Rivarola's wooden schools [11, 12], also allows external sunscreens to be placed away from the windows and doors and to protect the two room faces with mosquito nets as well.

In the future, the research group aims to work on refining the adaptation of the energy calculation software used in this project (Edilclima® compliant with ISO 52016-1:2017 and ISO 52022-1:2017). This software also includes the estimation of production from photovoltaics, which it is intended to make assessable in the future at other locations in the area of interest (besides Resistencia) for which the available database needs to be adapted and implemented.

Although the survey locations, building morphology, and climatic conditions are far from Europe and the EU Directive 2018/844 on the Energy Performance of Buildings (EPBD), it is interesting to count how many of the aspects included in the elements to be evaluated for the determination of the European Smart Readiness Indicator (SRI) are addressed by the module design: the SRI consists of 72 checks originating from 9 technical domains (heating, cooling, domestic hot water, ventilation, lighting, dynamic building envelope, electricity, electric vehicle charging, and monitoring & control), each of which must be managed to achieve 7 objectives (energy efficiency, maintenance and fault prediction, comfort, convenience, health, wellness and accessibility, occupant information, energy flexibility, and storage). The design of the building consisting of the proposed prefabricated modules appears to address about 40% of the 72 design aspects from the European Smart Readiness Indicator (SRI) (27 directly and 2 via add-on software), as in Table 3.

Of course, it is not possible to calculate SRI, since the reference smart building has not yet been defined for the climate zones of Argentina or Latin America.

Aggregating multiple modules can yield 26-pupil classrooms (2 modules side by side on the long side), *comedor* (canteen) or *biblioteca* (library), *salón de usos multiples* (multiple modules side by side on the short side and on the long side, as needed), as in Figures 4 and 5, to which coordinate modules intended for kitchen, warehouse, toilets, office, etc.

Further development of this research is aimed at building a prototype without furnishings and facilities to test the real issues of construction and transportation.

Table 3. EU smart readiness indicator (SRI): topics addressed in the module design.

Goals / Technical domains	energy efficiency	maintenance & fault prediction	comfort	convenience	health	well-being & accessibility	information to occupants	energy flexibility & storage
heating	✔		✔	✔	✔	✔	(✔)	✔
cooling	✔		✔	✔	✔	✔	(✔)	
domestic hot water	✔			✔	✔	✔		✔
ventilation			✔	✔	✔			
lighting	✔		✔	✔				
dynamic building env.								
electricity	✔			✔	✔		✔	✔
electric vehicle charging								
monitor & control			✔	✔			(✔)	✔

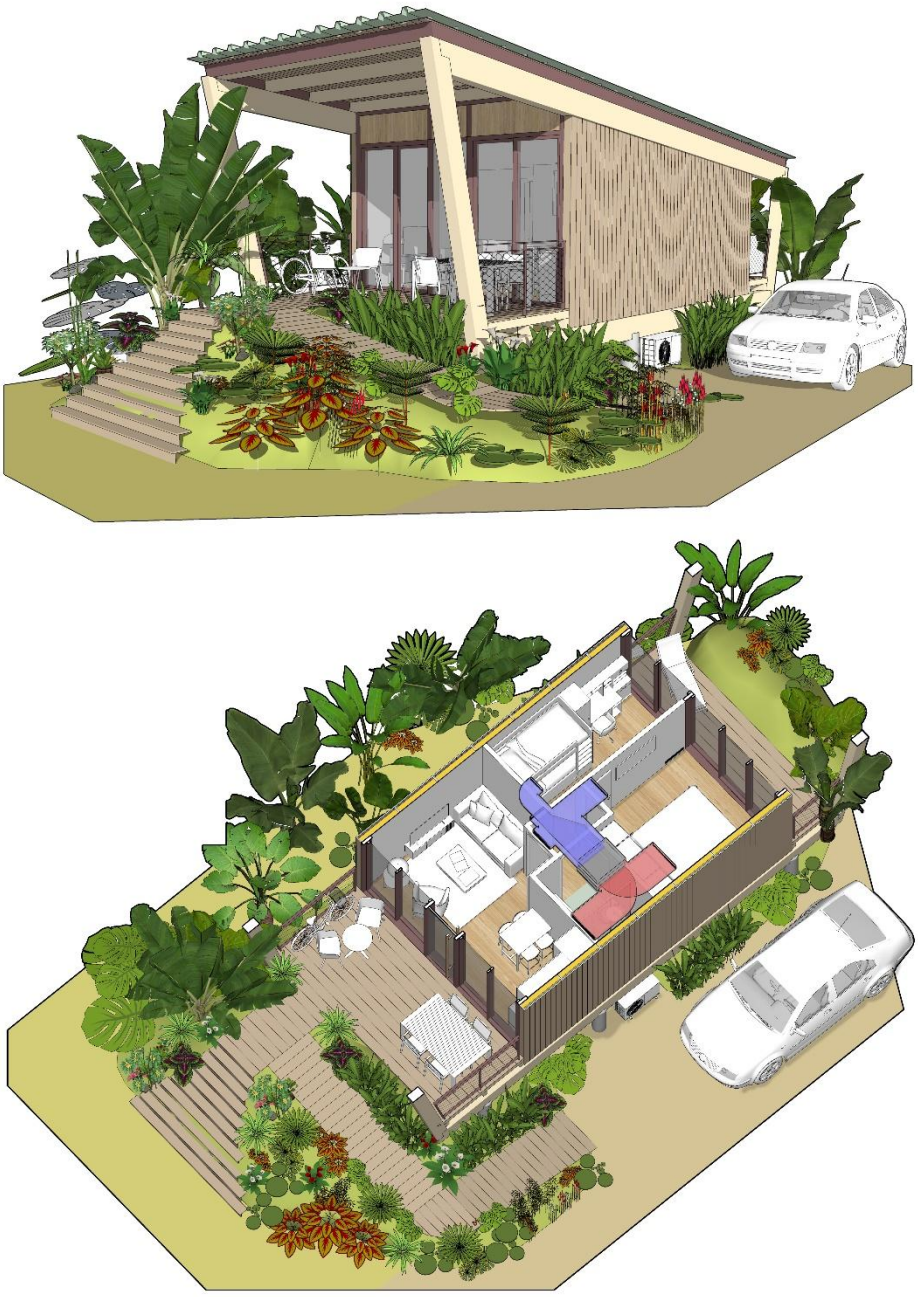


Fig. 3. 3D axonometric views of the minimal residential unit

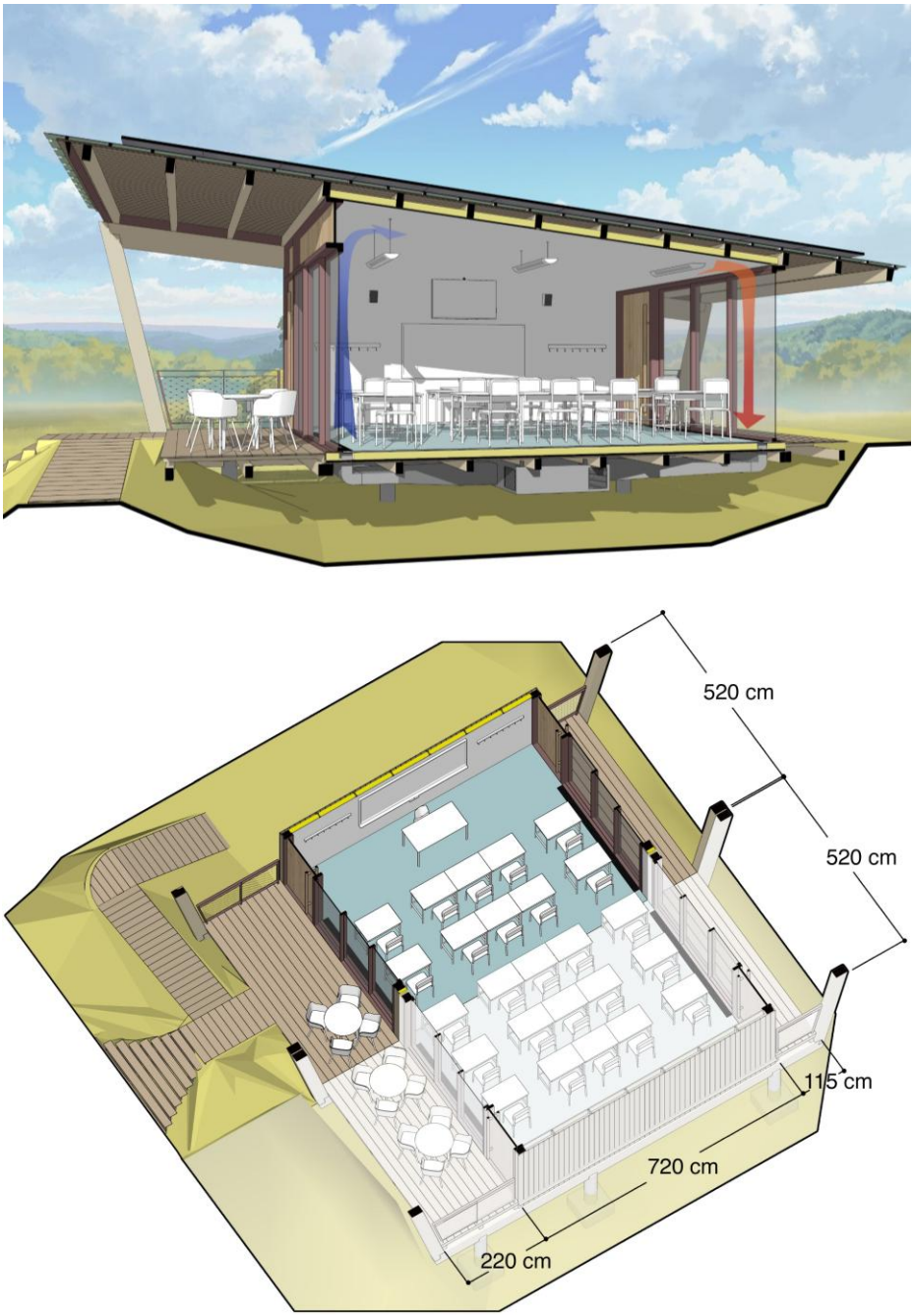


Fig. 4. Perspective section of the single module used as a classroom and 3D axonometric view of two modules aggregation side by side to create a 26-pupil classrooms



Fig. 5. 3D perspective view of a co-working space created by the aggregation of 4 modules side by side along the long side

Any individual module is suitable for and can be equipped as a collective toilet unit, as a locker room and shower unit (e.g., near sports facilities), as an office with secretariat, medical clinic with waiting room, etc., etc.

Having similar spaces to other proposals for prefabricated houses [13], it can also be intended as a minimal living unit, as in Figure 3, suitable for four people and equipped with a kitchenette over a living room with a sofa bed, so that its capacity can occasionally be increased to six people. This unit, replicated if necessary, can be useful as well as a residence for the school's janitors, or permanent teachers, as guest quarters for traveling teachers or for students living far away from the school.

The examples are offered to demonstrate the flexibility and modifiability of the uses of prefabricated modules, which, remaining energy self-sufficient, can grow in number without negatively impacting the environment and energy burdens. Because they are structurally identical, they can change their intended use and type of aggregation over time without much of the initial investment or materials being wasted, benefiting long-term sustainability.

Conclusions

The proposed prefabricated module is made of wood to improve its sustainability requirements and is also energy self-sufficient. It can be moved by a medium-sized truck and thus can be the answer to local school and community building requirements that can be easily adapted to local needs.

By adopting these practices, schools can become more responsive, efficient, and effective in serving and aggregating students and communities, ultimately improving the overall educational experience and outcomes. The multiple mode of module aggregation is the key to having public buildings that can evolve as the population for which they are intended evolves. It is the pivot to have a mix of public services (school,

community center, medical services, and so on) that is web connected and also maximizes the value for money of construction.

This that can become an “innovative practice” satisfies the initial instance of responding intelligently to the need for a more widespread and inclusive school infrastructure through the proposal of construction modules for sustainable and energy efficient buildings (SDG #4) and through the possibility of sending them where they are actually required, freely configuring them to meet the needs of the inhabitants: the research group trusts that in this way the smart city will spread and can ‘smartize’ the territory without functioning as an engine of depopulation of suburban and rural areas.

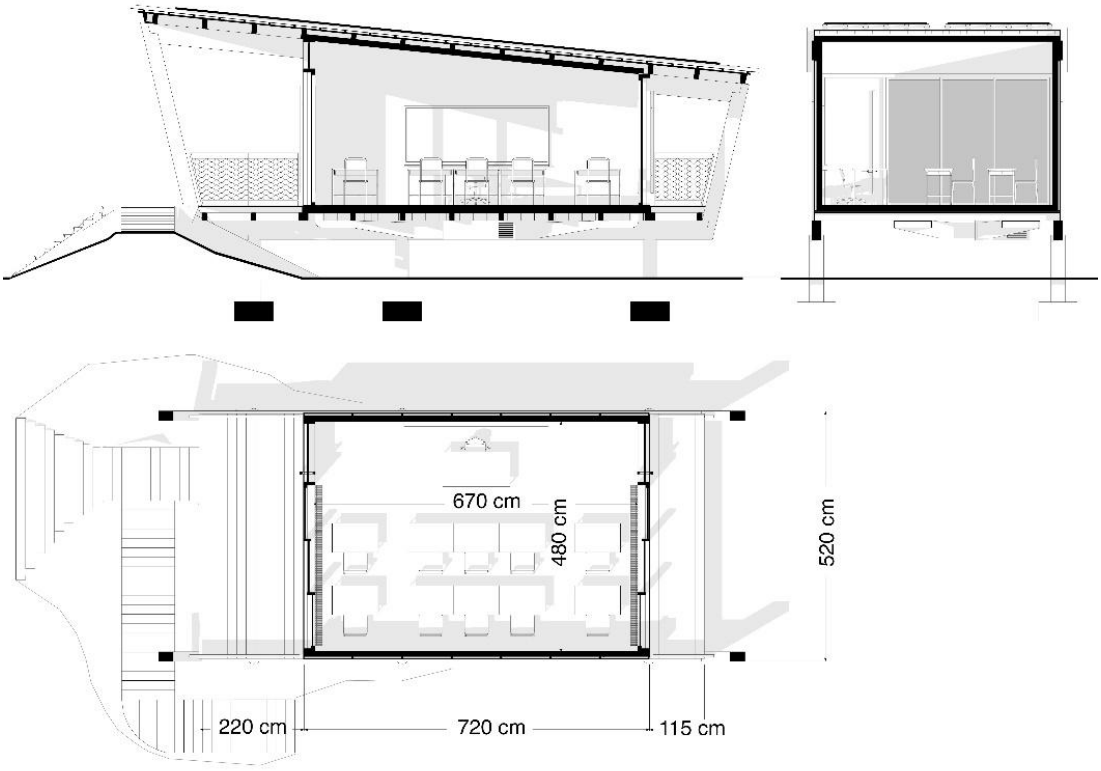


Fig. 6. Cross-sections and floor plan of the designed module

Disclosure of Interests. The authors have no competing interests to declare that are relevant to the content of this article. This study is part of the institutional research activity of the Politecnico di Torino and the Universidad Nacional del Nordeste.

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