

EMERGENCY SHELTER AND CONNECTIVITY FOR RURAL COMMUNITIES AFTER NATURAL DISASTERS: A CASE STUDY

JOSUÉ A. DIEPPA ORTIZ¹, CARLA LÓPEZ DEL PUERTO¹, GÉNESIS P. ACEVEDO GUZMÁN³, EIDEN O. GARCÍA TORRES², HUMBERTO E. CAVALLIN CALANCHE³, DANIEL RODRIGUEZ ROMÁN¹, and FABIO ANDRADE RENGIFO²

¹*Civil Engineering and Surveying Dept, University of Puerto Rico, Mayagüez, Puerto Rico*

²*Electrical and Computer Engineering Dept, University of Puerto Rico, Mayagüez, Puerto Rico*

³*School of Architecture, University of Puerto Rico, Río Piedras, Puerto Rico*

After a decade-long economic crisis and a series of major natural disasters, rural communities in Puerto Rico are grappling with significant gaps in vital services such as shelter, energy, water, and mobility. This particularly affects low-income elderly residents who rely on these services for an improved quality of life. A prime example of this situation is Corcovada, a rural community in the countryside of Puerto Rico which faces isolation and has a sizeable aging population. Its residents rely on themselves, their relatives, and other community members to provide transportation, as well as basic services like electricity for sustenance and medication maintenance. A site assessment was conducted, including solar irradiation, soil conditions, weather, and seismicity. This research presents an interdisciplinary design solution for modular emergency shelters for families in Corcovada, incorporating structural, solar energy, water use, and wind simulations. The emergency shelter module was designed with specific objectives and requirements: short-term accommodation for a family of four, expandability and collapsibility as needed, off-grid operation for water and energy during emergencies, and sustainability, resilience, affordability, and ease of assembly. Future endeavors involve the development of a mobility hub to reduce residents' reliance on private transportation.

Keywords: Resilience, Equity, Modular housing, Affordable, Vulnerability, Renewable energy, Rain-water collection.

1 INTRODUCTION

In recent years, Puerto Rico (PR) has been struck with multiple natural disasters and emergencies, including Hurricane María, the earthquakes in early 2020, and the COVID-19 pandemic, whose damages have cost billions of dollars and years of effort to recover (GAO 2021). These have dislocated and changed permanently the lives of its inhabitants, especially in vulnerable and isolated communities. While many areas of the island have suffered from extended lack of basic services, droughts, inability to access zones where landslides or floods have occurred, and lack of resources and supplies, high-risk communities such as Corcovada, a rural community in the countryside of PR which faces isolation and has a sizeable aging population, suffer the greatest impacts.

The Resilient Infrastructure and Sustainability Education Undergraduate Program (RISE-UP) is funded by the National Science Foundation (NSF) and hosted by the University of Puerto Rico.

The program lets participants learn to design sustainable and resilient infrastructure in an interdisciplinary environment where students of areas as Architecture, Civil and Electrical Engineering, and Surveying collaborate to develop solutions to emerging problems (Lopez del Puerto *et al.* 2021). In the last course of RISE-UP, a design of a shelter module for the community of Corcovada was developed. The present research's purpose is to design a temporary shelter for a natural disaster to families who have lost their homes. As part of the resilience and sustainability aspects, the shelters are designed so that they are modular in nature and easy to assemble, in such a way that anyone with basic tools may be able to build it.

2 DESIGN METRICS AND SITE ASSESSMENT

A primordial aspect of the present research is that the design of the shelter module is adaptable to multiple site and weather conditions, including varying topography, soil composition, wind, rain, and solar irradiation patterns. Equally important is that the module accomplishes the following operational goals to be considered effective: its target cost is 9,000 U.S. dollars (USD); it accommodates at least family of four and adapts to other family sizes; have autonomous energy and water supply systems; count with basic furniture and fixtures; its design encourages connectivity with the community; should be easy to build, storable, and transportable; and it implements passive ventilation mechanisms. Site assessment is conducted to assure the energy and rainwater collection services of the module can be met given the weather conditions of the community and consider a feasible design for the topography of the area.

2.1 Soil Conditions

Corcovada's site is composed of clay soils, with slopes ranging from 20 to 60 percent, and erosion factor, k , of 0.15 (USDA 2023). The value of k ranges between 0.02 and 0.69, where higher values indicate more susceptibility to erosion (USDA 2023). The sum of these factors creates a moderate erosion-related landslide risk in the site. Lastly, OSHA (2020) establishes that clayey soils, such as that of Corcovada, have from 48 to 144 kilopascals of stress capacity.

2.2 Solar Irradiation and Photovoltaic Electric Potential

Most areas in Puerto Rico receive enough solar irradiation to supply energy using photovoltaic (PV) panels throughout the lapse of a year. Data from PVWatts (2022) was retrieved, which showed an average electric irradiation of five kilowatt-hour per square meter per day is available for the site.

2.3 Weather Patterns

Being in the Caribbean, PR is prone to major natural weather events which can and have caused a long history of natural disasters. Events such as Hurricanes Irma and María in 2017, and their effects are recurrent and are expected to increase in frequency and intensity as an effect of Climate Change and will continue to represent a considerable risk (Municipio de Añasco and JP 2020). The current rain patterns were retrieved for the site using the National Water Information System of the USGS (2023). It is observed that in Corcovada it rains most of the year, and rain is especially substantial during the summer months.

2.4 Seismicity

PR is located on the border between the North American and Caribbean plates. The two plates collide at an angle, which results in a phenomenon called oblique subduction. This means that



there is a combination of subduction and lateral movement. Therefore, the entire island, including Corcovada, is susceptible to damage from earthquakes (Red Sísmica de Puerto Rico 2022).

3 ARCHITECTURAL AND CONSTRUCTIVE DEFINITION

The module designed is envisioned to be constructed with locally available resources and with simple member connections. For its design, a frame structural system was selected that holds lateral and vertical loads. The size of the module is 3.76 by 6.01 meters (12'-4" by 20') with two diagonal walls at a 45-degree angle, as shown in Figure 1. The space provides for the needs of bedroom, bathroom, and shared area. The materials used are wood, for structural and non-structural elements; steel, for structural connections; polyester, as a covering for the three front-facing walls of the module; and polyvinyl chloride (PVC), for the corrugated material on the roof and for the piping. The polyester textile to be used for the front walls will be opaque, water-repellent, and will resemble curtains that can be slid open and closed, allowing for access to the module, ventilation, and views.

The foundations are made of polypropylene-material foundation blocks with 816 kilograms capacity. These blocks are used principally in decks but are ideal for the module given the relatively low weight of it and the short duration it is expected to be used after a natural disaster. An instruction-like guide was developed for the construction of the modules, which included details on the connections to facilitate its construction. Once assembled, it can be closed by means of a hinge system, facilitating its transport and storage. The module should be assembled by the target community and stored prior to the disaster and be transported after an event. The soil preparation consists of excavating to insert the foundation blocks and columns 61 centimeters into the ground (as suggested by CIAPR (2021)) and developing the frame in which the module will rest. This is a relatively easy task, given a restriction of 50 percent slope. Once the foundation is built, the module is to be transported to site using a flatbed truck and moved to position using 318-kilogram rails to slide it over the foundation frame before connecting it.

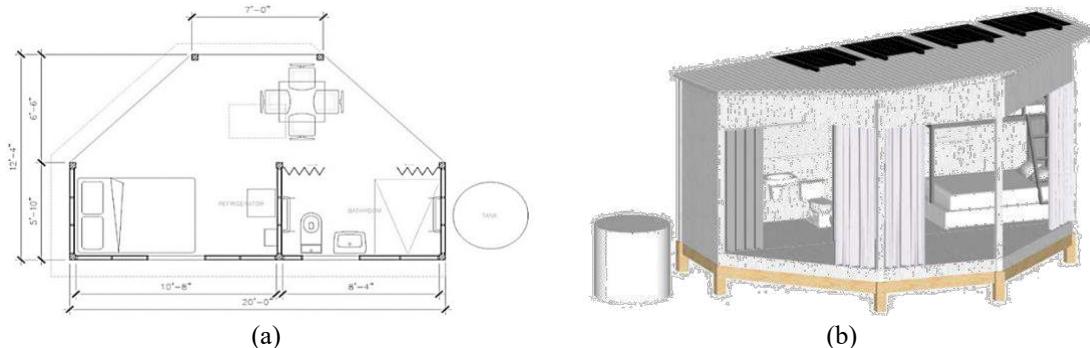


Figure 1. (a) Plan and (b) tridimensional views of the arrangement of the module.

3.1 Contemplating Social Factors

Through the design of the module, measures were implemented to consider the emotional state of affected individuals. Its shape enables it to be assembled in multiple arrangements between two to four modules, accommodating different or multiple families, which strengthens relationships in the community. The use of textiles and the freedom to open or close the space allow a connection with the outside and nature, evoking the feeling of a balcony. By means of materials, familiar and recognizable elements of a house are also alluded to. Also, the bathroom is adapted for handicap use.

4 PHOTOVOLTAIC ENERGETIC SYSTEM

An estimated consumption of 3048 Watt-hour per day and peak demand of 435 Watt is used for the design of a completely independent PV system with an autonomy of one day. The consumption considers a small fridge, two lightbulbs, a water pump, a fan, and an additional outlet. To supply the demand, five 200-Watt, 12-Volt PV panels, and three 12-Volt, 200-Ampere-hour batteries will be needed as shown in Figure 2. Estimates of autonomy are derived from analysis on the system's performance during the least productive month, which in PR is October. The system may be connected between modules, forming a microgrid, and thus becoming more efficient.

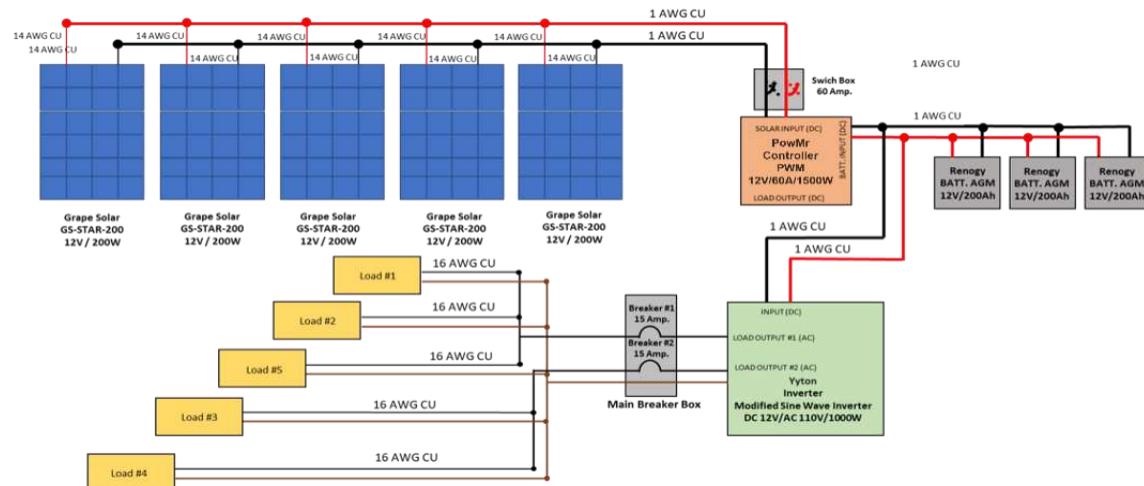


Figure 2. Energetic system diagram for one module.

5 RAINWATER COLLECTION SYSTEM

The Pan American Health Organization (PAHO 2013) established that, during an emergency, one person might consume 30 liters of water daily, including drinking, cooking, and personal hygiene. Community Enterprises Inc. (2019) establishes that the zone of Corcovada has a collection potential of 1630 liters per square meter per year. Given the 15.3 square meters (about the area of typical parking space) total roof area of the module, an autonomous collection system is unreasonable. Therefore, a proposed design for a partially autonomous water collection system with a 946-liter (250-gallon) tank is being considered, with arrangement of the system as shown in Figure 3.

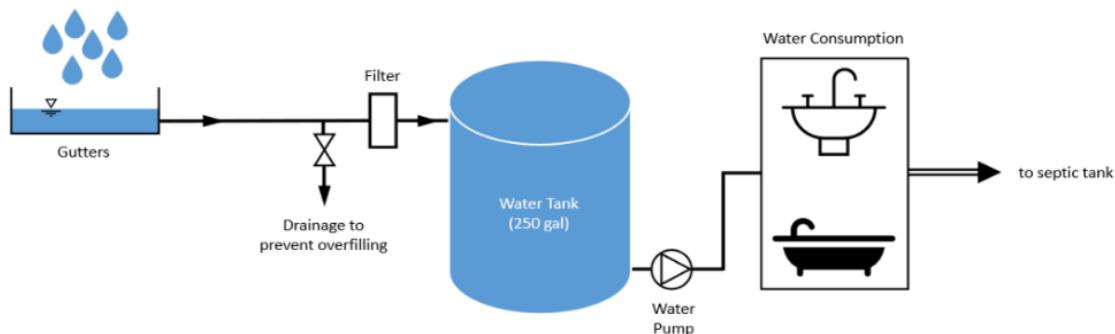


Figure 3. General Arrangement of the collection and piping system for one module.

6 SIMULATIONS

Multiple simulations were conducted to test the structural integrity of the module, feasibility of the PV generation and rainwater collection systems, ventilation, and illumination. The system was modelled in SAP 2000 (2023), with the corresponding properties shown in Tables 1 and 2. For simplification, wood was simulated as an isotropic material. The module was tested under multiple load combinations, as established in the PR Building Code (ICC 2018). The model's deflections comply with the maximum allowable deflections, and the maximum drift of 0.6 percent is under the maximum allowable drift of one percent (ICC 2018). Therefore, it is concluded that the structure behaves satisfactorily.

Table 1. Material properties used to model the shelter in SAP 2000 (2023).

Material	Unit Weight (kg/m ³)	Modulus of Elasticity (GPa)	Poisson's Ratio	Thermal Expansion Coefficient (1/°C)	Shear Modulus, G (GPa)
Wood	400.00	12.000	0.3	11.7×10^{-6}	4.615
PVC	55.36	2.746	0.3	11.7×10^{-6}	1.056

Table 2. Parameters used for SAP 2000 (2023) structural simulations.

Parameter	Value	Type of Simulation
Soil Type	D	
F _a Site Coefficient	1.022	
F _v Site Coefficient	1.843	
0.2 s Spectral Acceleration	1.195	Seismic
1 s Spectral Acceleration	0.457	
Damping	5%	
Design Wind Velocity	225 km/h (140 mph)	
Exposure Category	C	
Topography Factor, K _{zt}	0.29	
Gust Factor, G	0.85	Wind
Direction Factor, K _d	0.85	
Pressure Coefficient, C _p	0.8	

The energy simulations were conducted assuming the generation of October, which has the lowest irradiation of the year in the site, and assuming an initial charge of the batteries of 50 percent. Assuming all consumption and generation, at the end of the day, the batteries end with 51 percent of charge, as shown in Figure 4. Given the results, it is concluded that the system functions as intended and has the expected day of autonomy.

Water simulations were conducted, finding that, for an average year, the system has an autonomy of at least a week. For ventilation and illumination simulations, assuming the textile walls of the module are open, air will flow freely through the module, and it will receive mostly indirect light. Two windows on the rear façade of the module help create ventilation. In the night or when the curtains are closed, the lightbulbs and fans will supply the ventilation and illumination needed.

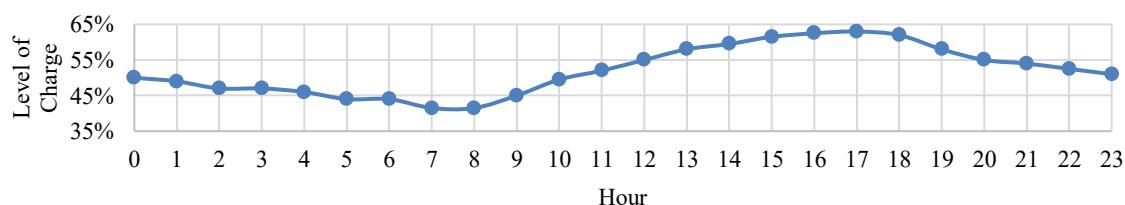


Figure 4. Average batteries' level of charge for one shelter module in the month of October.

7 CONCLUSIONS

The modular shelter developed, and its solar power and rainwater collection systems provide basic services and accommodations, accomplishing to be affordable, structurally sound for the frequent natural events seen in the area, and self-sufficient when electricity and water services are not available. Future research could study the integration of mobility within and outside the community as an articulated effort in rendering more resilient communities in face of natural disasters, the climate change, and the need to safe housing and security of essential services.

Acknowledgments

This material is based upon work supported by the National Science Foundation (NSF) under Grants No. 1832468, 1832427, and 2228601. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the NSF. The authors are greatly thankful to their RISE-UP peers Melissa Herazo Ramirez, Jose Batlle Miranda, and the Comité Comunal De Corcovada for their contributions towards the development of the present research.

References

CIAPR, *Rehabilitación Sísmica para Viviendas en Puerto Rico*, Ciapr.org, September 10, 2021. Retrieved from <https://www.ciapr.org/wp-content/uploads/2021/09/Rehabilitacion-Sismica-de-Viviendas.pdf> on May 3, 2023 (in Spanish).

Community Enterprises Inc., *Manténgase Seguro: Una Guía Para el Diseño de Viviendas Resilientes en Comunidades Isleñas*, Keepsafeguide.enterprisecommunity.org, January 15, 2019. Retrieved from https://keepsafeguide.enterprisecommunity.org/sites/default/files/chapter_pdfs/Keep_Safe_Spanish.pdf on May 2, 2023 (in Spanish).

GAO, *Puerto Rico Recovery: FEMA Made Progress in Approving Projects, But Should Identify and Assess Risks to the Recovery (GAO-21-264)*, gao.gov, May 17, 2021. Retrieved from <https://www.gao.gov/assets/gao-21-264.pdf> on September 1, 2023.

ICC, *2018 Puerto Rico Building Code*, 2018.

Lopez del Puerto, C., Cavallín, H., Perdomo, J., Muñoz, J., Suárez, M., and Vázquez, D., *RISE-UP: An Interdisciplinary Learning Tool to Generate Sustainable and Resilient Infrastructure*, RIDNAIC, 19-20(17), 2021. Retrieved from https://www.scipedia.com/public/Puerto_et_al_2021b on July, 2023.

Municipio de Añasco and JP, *Plan de Mitigación contra Peligros Naturales*, Jp.pr.gov, July 27, 2020. Retrieved from <https://jp.pr.gov/wp-content/uploads/2021/10/Anas-Approved-HMP-200805.pdf> on March 7, 2023 (in Spanish).

OSHA, *Safety and Health Regulations for Construction subpart P: Excavations appendix A: Soil Classification (1926 Subpart P App A)*, Osha.gov, January 5, 2020. Retrieved from <https://www.osha.gov/laws-regulations/standardnumber/1926/1926SubpartPAppA> on April 14, 2023.

PAHO, *Notas Técnicas sobre Agua, Saneamiento e Higiene en Emergencias: Cantidad de Agua Necesaria para Emergencias*, Paho.org, December 5, 2013. Retrieved from <https://www.paho.org/es/documentos/cantidad-agua-necesaria-para-emergencias> on May 12, 2023 (in Spanish).

PVWatts, *PVWatts Calculator*, NREL, Pvwatts.nrel.gov, January 22, 2022. Retrieved from <https://pvwatts.nrel.gov/pvwatts.php> on February 14, 2023.

Red Sísmica de Puerto Rico, *Informe de la Actividad Sísmica en la Región de Puerto Rico e Islas Vírgenes Durante el Mes de Febrero de 2022*, Redsismica.uprm.edu, University of Puerto Rico at Mayagüez, January, 18, 2022. Retrieved from <https://redsismica.uprm.edu/spanish/sismicidad/reportes/2022/boleFebrero2022.pdf> on March 2023 (in Spanish).

SAP 2000 software, retrieved from <https://www.csiamerica.com/products/sap2000> on April 2023.



USDA, *Soil Classification Map by Composition in Corcovada, Añasco*, Natural Resources Conservation Service Web Soil Survey, [Websoilsurvey.sc.egov.usda.gov](https://websoilsurvey.sc.egov.usda.gov), March 19, 2023. Retrieved from <https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx> on March 25, 2023.

USGS, *Site Map for USGS 50144000 RÍO GRANDE DE ANASCO NR SAN SEBASTIAN, PR*, National Water Information System: Web Interface, [Waterdata.usgs.gov](https://waterdata.usgs.gov), January 7, 2023. Retrieved from https://waterdata.usgs.gov/nwis/nwismap/?site_no=50144000&agency_cd=USGS on February 17, 2023.