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Addressing Post-Disaster Challenges and Fostering Social Mobility through Origami Infrastructure and Construction Trade Education

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Abstract: Natural disasters devastate property and infrastructure systems, impeding sustainable development. Low-income communities, due to economic, physical, and social disparities, face heightened exposure and vulnerability. These communities endure severe and long-lasting infrastructure damage, experiencing a fourfold increase in deaths per disaster and delayed recovery efforts. Consequently, they resort to constructing informal housing and infrastructure, worsening post-disaster challenges and vulnerabilities. This study aims to address post-disaster challenges in low-income communities by proposing two novel approaches that remain understudied despite their significant potential: (1) a short-term solution of origami temporary emergency housing for swift shelter post-disaster, enabling a return to routine activities while homes and infrastructure systems are being repaired or rebuilt; and (2) a long-term solution, including effective pedagogy, such as teaching methods and instructional tools, to educate and train low-income individuals to aid in sustainable post-disaster reconstruction while providing the added benefit of social mobility. To validate the feasibility of origami TEH and the need and effectiveness of the pedagogy, a survey among architecture, engineering, and construction experts in Puerto Rico, a region prone to natural disasters, was conducted. The results, analyzed using statistical measures including descriptive statistics and ordered probit regression analysis, emphasize the urgent need for sustainable TEH that can be quickly assembled and education for low-income individuals in construction trades. Implementing these solutions will significantly impact communities by addressing post-disaster challenges and promoting social mobility and job equity.

Keywords: construction trades; disaster management; informal infrastructure; natural disasters; origami temporary emergency housing; sustainable and resilient reconstruction; sustainable infrastructure; social mobility

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1. Introduction

Natural disasters stem from the combination of natural hazards, along with the exposure and vulnerabilities that endanger communities incapable of withstanding and coping with such threats [1]. Natural disasters encompass (1) extreme geological disasters, including earthquakes, volcanic eruptions, and geophysical landslides; and (2) climate- and weather-related disasters, including hurricanes, tornadoes, floods, storms, hydrometeorological landslides, wildfires, extreme temperatures, and drought [2]. However, characterizing the impacts of natural hazards and disasters can be challenging, since a single hazard agent can trigger several threats [1]. For instance, volcanic eruptions can affect communities and infrastructure through ash fall, explosive eruptions, lava flows, tsunamis, floods, mudflows, and forest fires [1,3,4]. Similarly, hurricanes can cause casualties and damage via wind, rain, storm surge, and flooding [1,5].

Natural disasters stand as the main source of damage and destruction to property and infrastructure systems, hindering sustainable development, as well as social and economic progress [6,7]. Over the past two decades, there have been 7.348 natural disasters recorded worldwide. These events have resulted in economic losses exceeding USD 2.97 trillion, claimed 1.23 million lives, and affected 4.2 billion individuals. The impacts on individuals and communities include injuries and damage to human health, loss of income, destruction of homes and infrastructure systems, homelessness, displacement, and reduced access to food, electricity, and water [6–9].

Natural disasters pose threats to all countries and communities. However, the resulting losses and damages are not equally distributed due to physical, social, and economic inequities [10,11]. Low-income communities not only lack education, income, and resources to prevent, prepare for, and effectively respond to natural disasters, but they are also more exposed and vulnerable to such events [2,11,12]. These communities often settle in riskier areas, especially where land is scarce, because the cost of land is lower, increasing their exposure to natural disasters [12–14]. Furthermore, they often live in settlements that are poorly designed and constructed, often built using informal construction methods, lacking the involvement of contractors, structural expertise, professional guidance, quality control, or appropriate construction methods [12,15,16]. As such, informal settlements are more susceptible to the impacts of natural disasters [2,9]. Consequently, these communities are more vulnerable to natural disasters and endure not only severe and long-lasting infrastructure damage but, most importantly, a fourfold increase in deaths per disaster [2,17]. Most fatalities result from infrastructure collapse. Therefore, implementing safer construction practices can help prevent losses and reduce future fatalities [6,18–20].

To compound the problem, the frequency and intensity of natural disasters, along with their associated damages and losses, have exhibited a consistent increase [21–28]. Additionally, low-income communities often experience delayed disaster recovery, with the implementation of emergency housing and relief efforts taking several months, or even years [28–30]. Consequently, natural disasters lead to prolonged and widespread homelessness, health issues, and a housing and infrastructure crisis, which are often already prevalent in low-income communities but are greatly exacerbated by such events [16]. This can translate into informal infrastructure reconstruction, as affected individuals will use their own resources and efforts to rebuild their homes and/or infrastructure systems to recover from the disaster [16].

Access to housing is a basic human need and is crucial for living, protection, and overall wellbeing [31,32]. Temporary emergency housing (TEH) provides a means for those affected by natural disasters to cope better, enabling a sustainable return to regular activities while damaged infrastructure and homes are repaired or reconstructed [33]. Therefore, it is crucial to ensure that all victims have access to a safe, livable, resilient, and sustainable shelter capable of withstanding climate and environmental challenges such as high winds, severe rainfall, and earthquake aftershocks in the aftermath of a natural disaster [21,34–36]. To achieve this, temporary shelters should be not only readily accessible and available following natural disasters but also easy and quick to construct, lightweight, and deployable to facilitate their transportation to affected areas [37,38]. Moreover, they should be affordable, with costs proportionate to the intended duration of use, as well as sustainable to address growing environmental concerns and the enormous environmental footprint of the built environment [36–42]. To meet sustainability goals, shelters should be transferable, adaptable, or recyclable once no longer needed [37,38,42]. To this end, it is imperative to investigate innovative TEH alternatives, focusing on resilience, functionality, ease of assembly, cost-effectiveness, sustainability, and ease of transportation [35,43,44]. Origami TEH offer an effective and efficient solution to construction challenges in challenging environments, including post-disasters [45–49]. These structures exhibit geometric versatility, adaptability, flexibility, and functionality and can be easily and quickly assembled [47]. Moreover, their lightweight and foldable design enable easy transportation into post-disaster environments, where access may be difficult or limited [44,50]. Additionally, origami shelters can be constructed from white polypropylene, which has a 20-year lifespan [51]. This material is both cost effective and fully recyclable through mechanical processes, enhancing its sustainability. Furthermore, its durability ensures the shelters' reusability and transferability [51]. Despite the potential of origami to provide a short-term solution to the post-disaster housing crisis, offering victims a quick, secure, and habitable shelter, this solution remains understudied.

Furthermore, delayed disaster recovery exacerbates the post-disaster housing and infrastructure crisis, and the recovery period for low-income communities, including repair and reconstruction, after a major natural disaster can take several years [29,30]. Consequently, natural disasters lead to informal reconstruction where individuals rebuilt their homes themselves as an effort to recover from the disaster, exposing them to great danger [16,29,30,52]. As such, supporting low-income communities by providing them with the necessary education, training, techniques, and expertise related to construction trades and methods is crucial not only to aid in sustainable and more resilient post-disaster infrastructure reconstruction but also for community wellbeing. Additionally, such education and training promote social mobility and job equity, helping low-income individuals and underrepresented workforces find better job opportunities.

Despite the importance of innovative solutions to address post-disaster challenges, including origami temporary emergency housing (TEH) and construction trade education for more resilient post-disaster reconstruction, these approaches remain understudied. To address these gaps, the goal of this study was to propose: (1) a short-term solution involving origami TEH to quickly shelter potential victims post-disaster, offering them safe and habitable shelter that enables them to resume their daily routines while their homes are being repaired or rebuilt; and (2) a long-term solution, which involves effective pedagogy to equip low-income individuals with the necessary education, training, techniques, technologies, and expertise to contribute to sustainable and resilient post-disaster infrastructure reconstruction and promote social mobility. To evaluate the feasibility of origami TEH as well as the effectiveness of the pedagogy, the authors conducted a survey among architecture, engineering, and construction (AEC) experts in Puerto Rico. Puerto Rico was selected as the focal region due to its frequent exposure and high vulnerability to natural disasters, including earthquakes, hurricanes, severe storms, and flooding [53,54]. This island grapples with severe damage, prolonged recovery periods, and significant challenges arising from limited financial resources, economic disparities, high poverty levels, and prevalent informal construction practices, all of which exacerbate its vulnerability to such events [54,55]. Despite being an unincorporated territory of the United States, which entitles its citizens to federal recovery assistance, disaster recovery and relief efforts in Puerto Rico are slow and insufficient [16,56]. In fact, 45% of Puerto Rico's population lives below the poverty level, and the island is ranked among the top ten territories based on the economic losses they incurred as a percentage of their gross domestic product (GDP), with a 3.5% loss [8,57]. The findings of this study benefit communities and stakeholders by addressing post-disaster challenges through an innovative TEH solution while also promoting social mobility and job equity through education and training.

2. Materials and Methods

This research was guided by four research questions: (1) What is the anticipated duration of disaster recovery following a major natural disaster in Puerto Rico? (2) What are the essential characteristics of TEH necessary to effectively address the major challenges, vulnerabilities, and crucial needs of low-income communities after a natural disaster, thereby aiding in quicker and more effective disaster recovery? (3) What are the main issues of informal construction? (4) What deficiencies exist in the construction trade knowledge of low-income individuals and how can we equip them with effective education, training, construction techniques, technologies, and expertise to contribute to more resilient post-disaster reconstruction?

This research addressed these four research questions by surveying 54 AEC experts, as well as other relevant professionals from diverse fields such as education, business, finance, and social sciences in Puerto Rico. These professionals possess significant knowledge in natural disasters and their effects on infrastructure and communities, owing to the frequent exposure and high vulnerability of these regions to various natural disasters, including earthquakes and hurricanes. Consequently, AEC education in Puerto Rico is intricately designed to address the specific challenges posed by such disasters. Given their specialized knowledge, the findings gleaned from this sample are indicative and reflective of the broader challenges and needs faced by the community, making it a representative subset for the study's objectives. The research used a purposive sampling process to collect data, which involves selecting individuals for the sample based on the researcher's judgment of their relevance given their knowledge and experiences. This study employed a mixed-methods sequential explanatory design to collect and analyze both quantitative and qualitative data.

2.1. Survey Design

The administered survey comprised a demographic section and a total of three main sections. The first section contained seven questions aimed at eliciting experts' experiences and opinions regarding natural disasters, as well as the major challenges, vulnerabilities, and crucial needs of low-income communities post-disaster. The initial five questions queried whether experts had encountered a major natural disaster and requested open-ended responses detailing their experiences if they had faced such an event. Additionally, they were inquired about their involvement in disaster management, the duration of disaster recovery, and the timeframe for all affected individuals to gain access to TEH in Puerto Rico. Following these questions, two further questions focused on understanding the challenges, vulnerabilities, and critical needs of low-income communities after a natural disaster.

The second section of the survey consisted of five questions designed to explore how TEH could aid in disaster recovery and relief efforts. Two questions evaluated the key characteristics that such shelters should possess. The subsequent three questions aimed to determine the importance of investigating TEH, whether TEH could enhance the health and wellbeing of disaster victims, and the suitability of a compact, foldable origami shelter as a TEH solution post-disaster.

The third section of the survey included five questions aimed at understanding the main challenges of informal construction and the benefits of educating and training low-income individuals in construction trades and basic construction methods. Two questions focused on identifying the primary problems of informal construction and whether experts believed that educating and training low-income individuals, who often reside in self-built informal settlements due to resource constraints, in construction trades and basic construction knowledge could contribute to a more resilient post-disaster reconstruction. Subsequently, two questions aimed to identify effective pedagogy, including construction trade courses, teaching methods, and instructional tools that should be employed to adequately educate and train low-income individuals to facilitate a more resilient post-disaster reconstruction. The final open-ended question aimed to determine the resources lacking in low-income communities.

The survey data were analyzed using both quantitative and qualitative methods. The study employed diverse visualization techniques including (1) bar charts to graphically represent categorical data; (2) box plots to display Likert scale data; and (3) word clouds generated using NVivo 14 to represent qualitative data. In the word clouds, the size of words is proportional to their frequency in the text. NVivo 14 is specialized qualitative analysis software, offering distinct features that include enhancing transparency and confidence in the synthesis of findings [58].

The authors conducted various statistical measures to assess the consistency, reliability, and adequacy of the sample size, including (a) the Kaiser–Meyer–Olkin (KMO) measure of sampling adequacy; (b) the Bartlett's test of sphericity to evaluate if there is sufficient correlation among the variables to proceed with factor analysis; and (c) the Cronbach's alpha test to assess the reliability of the questionnaire [59].

Kaiser–Meyer–Olkin (KMO) measure of sampling adequacy. The KMO test is a statistical tool used to assess the sufficiency of the sample size for both the overall model and each individual variable within the model. The formula for the KMO test is as follows:

$$KMO_j = \frac{\sum_{i \neq j} R_{ij}^2}{\sum_{i \neq j} R_{ij}^2 + \sum_{i \neq j} U_{ij}^2} \quad (1)$$

where U_{ij} is the partial covariance matrix and R_{ij} is the correlation matrix. The covariance matrix is a square matrix that represents the covariance between each pair of variables in a dataset. It quantifies the degree to which two variables change together. The correlation matrix is closely related to the covariance matrix. It contains the correlation coefficients between pairs of variables, which indicate the strength and direction of their linear relationship [60,61]. KMO values range from 0 to 1. For sample sizes under 100, a value of 0.6 or higher means that the sampling was adequate.

Bartlett's test of sphericity. Bartlett's test of sphericity examines the null hypothesis H_o that the variables are orthogonal, implying that the original correlation matrix resembles an identity matrix, indicating that the variables are unrelated and therefore not suitable for uncovering an underlying structure. The alternative hypothesis H_1 posits that the variables are not orthogonal, indicating sufficient correlation and a significant deviation of the correlation matrix from the identity matrix. Sphericity is assessed through Bartlett's test with the following formula:

$$\chi^2 = \left(n - 1 - \frac{2p+5}{6}\right) X \ln|R| \quad (2)$$

where n is the total sample size, p is the number of variables, and R is the correlation matrix. A significance level of less than 0.05 indicates the adequacy of the factor analysis.

Cronbach's alpha. The reliability of the questionnaire was assessed using Cronbach's alpha test. This test offers a straightforward method to evaluate the consistency of scores when multiple items measure the same underlying concept. Internal consistency is quantified by Cronbach's alpha, which ranges from 0 to 1. A Cronbach's alpha value exceeding 0.7 is generally considered acceptable. A high alpha value indicates a strong correlation among the test items. Cronbach's alpha can be expressed by the following formula:

$$\alpha = \frac{n\bar{r}}{1 + \overline{r(n-1)}} \quad (3)$$

where n refers to the number of items and $\bar{r}$ is the mean correlation between items.

2.2. Ordered Probit Regression Analysis

The study used a statistical ordered probit regression analysis to determine the impact of diverse variables on the adequacy of origami shelters as a TEH solution post-disaster. This analysis is appropriate for examining a categorical dependent variable to identify which independent variable has a statistically significant impact on it. Ordered probit regression analysis is particularly suitable for cases where the dependent variable is ordinal and has more than two potential outcomes, such as categories like not a good solution, fair, good, considerably good, and excellent solution [62]. This method allows for the generalization of cases with multiple ordered outcomes. For this model, the dependent variable is defined as the adequacy of origami shelters as a solution for TEH post-disaster. The independent variables include (1) the different challenges and vulnerabilities that low-income communities face post-disaster, including lack of housing/shelter, lack of water and/or food, lack of electricity, feeling unsafe, health issues, mental health, and delayed disaster recovery; (2) the crucial needs of low-income communities post-disaster, including having a shelter, returning to work and routine activities, having water and food, having access to electricity, and emotional recovery; and (3) the key characteristics that TEH should have, including easy and quickly assembly, lightness, readily availability, deployability, easy storage of units, large production capacity, reusability, recyclability, transferability, sustainability, low environmental impact, and easy disassembly. The ordinal probit regression analysis uses these parameters in the following equation:

$$y_i^* = X_i\beta + \varepsilon \quad (4)$$

where y_i^* is a latent variable measuring the adequacy of origami shelters as a solution for TEH post-disaster for the ith participant; X_i is a (k × 1) vector of observed nonrandom explanatory variables; β is a (k × 1) vector of unknown parameters; and error factor (ε) captures the reality that the fact that origami shelters are an adequate solution post-disaster is not perfectly predicted by the regression equation. Therefore, the observed importance of this TEH solution, y_i, is determined from the model according to:

$$y_i. = \left\{ \begin{array}{c} 1\ if -\infty \leq\ y_i^* \leq \mu_1\ (Not\ a\ good\ solution) \\ 2\ if\ \mu_1 \leq\ y_i^* \leq \mu_2\ (Fair) \\ 3\ if\ \mu_2 \leq\ y_i^* \leq \mu_3\ (Good) \\ 4\ if\ \mu_3 \leq\ y_i^* \leq \mu_4\ (Considerably\ good) \\ 5\ if\ \mu_4 \leq\ y_i^* \leq \mu_5\ (Excellent\ solution) \end{array} \right\} \quad (5)$$

Equation (4) relies on both theoretical and statistical principles to assume a linear relationship, facilitating the modeling of the latent variable representing the adequacy of origami shelters as a TEH solution post-disaster. This assumption allows for the evaluation of how changes in the independent variables influence the ordinal outcome categories, thereby facilitating interpretation of their effects on the adequacy of origami shelters. Furthermore, in the equation, the partial change in y^* with respect to X_i is β_i units. This implies that for a unit change in X_i, y^* is expected to change by β_i units, holding all variables constant. Additionally, the significance test uses the z-score to depict the expected behavior of the mean in a dataset with a certain number of observations. The p-value indicates the confidence level, in terms of correlation, between independent variables and the dependent variable. In this study, a confidence interval of 95% is assumed, corresponding to a z-score of 1.96. Consequently, significance is attained at an alpha level less than or equal to 0.05.

3. Results

This section presents the results associated with the responses of 54 AEC experts, as well as other relevant professionals from diverse fields such as education, business, finance, and social sciences from Puerto Rico. This research employed a mixed-methods sequential explanatory design to collect and analyze both quantitative and qualitative data from experts. The recorded data included a diverse group of experts, as presented in Figure 1, which included thirty-one males, sixteen females, and one non-binary individual, as well as eighteen experts with a bachelor's degree, twenty-four experts with a master's degree, two experts with a doctoral degree, two experts with a professional degree, and two with other degrees. Professional degrees and others included professional engineer (PE) and associate degrees. These experts have extensive knowledge about natural disasters and their effects on both infrastructure and communities, stemming from the frequent exposure and heightened vulnerability of this region to various natural disasters, including hurricanes, earthquakes, severe storms, and flooding. Consequently, AEC education in Puerto Rico is intricately customized to tackle the specific challenges presented by natural disasters.

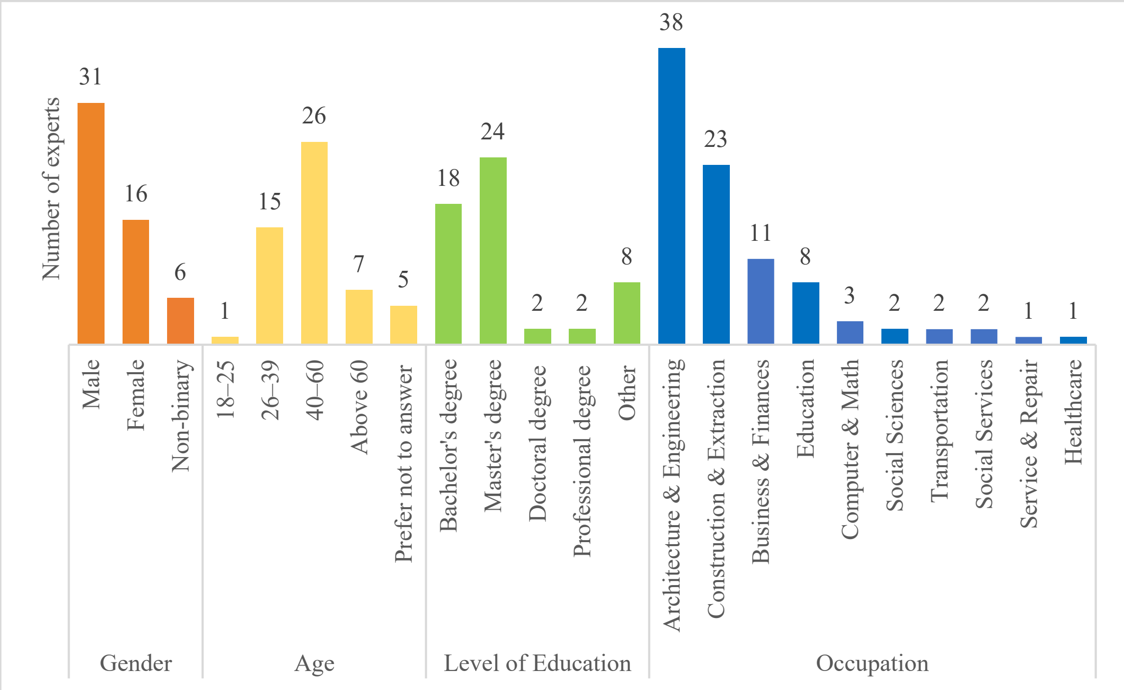

Figure 1. Socio-demographic background, $n = 54$.

The first section of the survey contained seven questions aimed at eliciting experts' experiences and opinions regarding natural disasters, as well as the major challenges, vulnerabilities, and crucial needs of low-income communities post-disaster. The results of this study, presented in Figure 2, show that (1) among the 54 Puerto Rican experts surveyed, 51 have experienced a major natural disaster and 28 experts have participated in disaster management and/or recovery; (2) approximately 60% of the surveyed experts from Puerto Rico, totaling 32 individuals, consider the duration of recovery following a significant natural disaster on the island to exceed 1 year; and (3) Puerto Rican experts have differing views on the duration it takes for all affected individuals and communities to access TEH following a natural disaster.

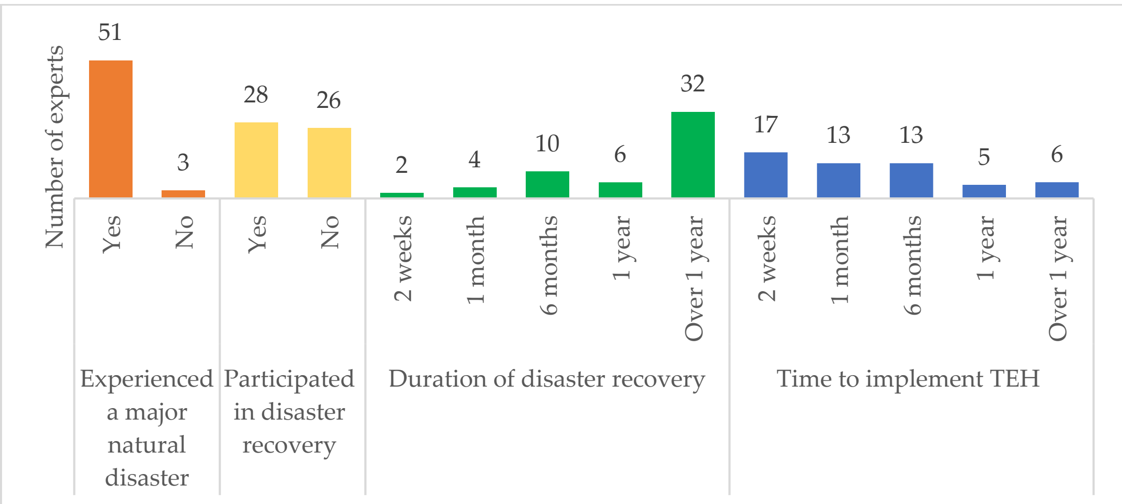

Figure 2. Experts' experience and opinions regarding natural disasters and disaster recovery.

Additionally, experts who had experienced a major natural disaster were asked an open-ended question about the physical damage to infrastructure and the social and economic impacts on the community resulting from these events. To analyze the insights provided by these experts, the authors utilized NVivo 14 software. A word cloud, presented in Figure 3, was chosen as the visualization technique because it effectively summarizes and highlights the most frequent terms within the experts' answers, providing a quick and intuitive overview of the key concepts expressed by them. As may be observed in Figure 3, the words 'power', 'damage', 'water', and 'loss' were the most frequently occurring. Other high-frequency words included 'lost', 'hurricane', 'roads', 'flooding', and 'months'. This suggests that Puerto Rico is highly affected by natural disasters, including hurricanes and earthquakes, resulting in not only flooding and power failure but also severe and long-lasting damage to buildings and infrastructure systems, as well as losses.

Figure 3. Word cloud of experts' experience with major natural disasters.

Figure 4 highlights the major challenges and vulnerabilities and Figure 5 the crucial needs that low-income communities face post-disaster. The results are presented using box plots, where the box spans from the first quartile (Q1) to the third quartile (Q3) of the distribution. The median is depicted by a horizontal line, while the mean is represented by an "x", and the whiskers indicate the minimum and maximum values. The major challenges and vulnerabilities, presented in Figure 3, include (1) lack of water and food, reflecting a mean of 4.8; (2) lack of housing, with a mean of 4.6; (3) delayed disaster recovery, with a mean of 4.4; (4) health issues, reflecting a mean of 4.3; and (5) lack of electricity, yielding a mean of 4.3. The crucial needs, presented in Figure 4 include: (1) having water and food, reflecting a mean of 4.9: and (2) having a shelter, with a mean of 4.8.

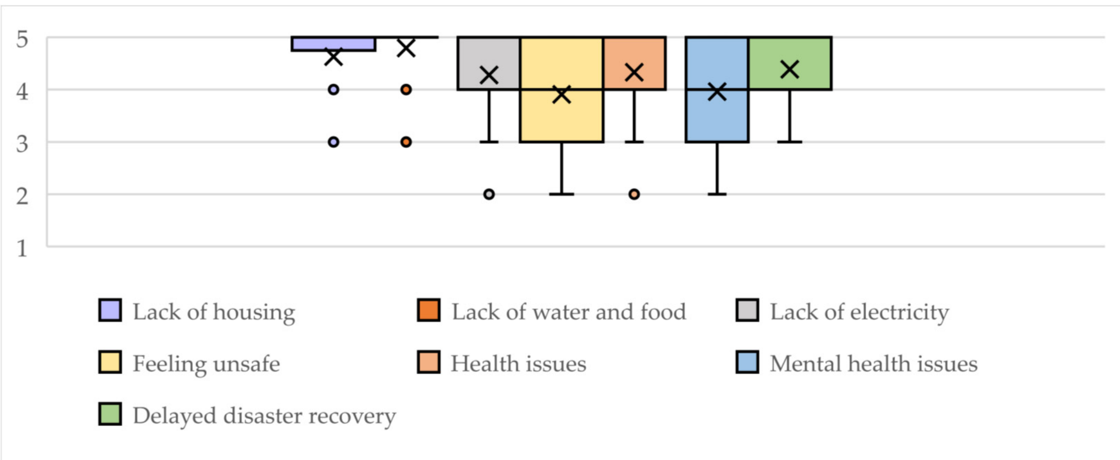

Figure 4. Major challenges and vulnerabilities of low-income communities post-disaster.

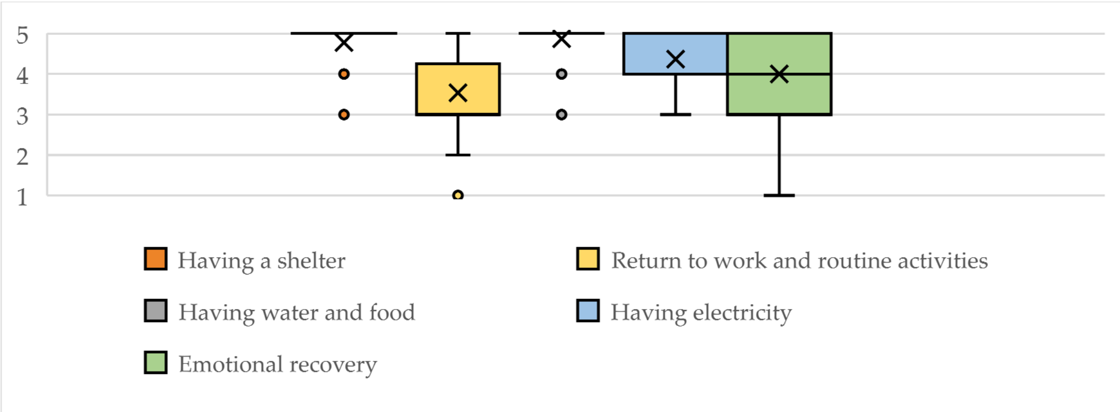

Figure 5. Crucial needs of low-income communities post-disaster.

The second section of the survey explored how TEH could aid in disaster recovery and relief efforts. The results of this section, presented in Figure 6, underscore the significance of investigating TEH as a post-disaster solution, with nearly all surveyed experts, except one, emphasizing its critical importance. Furthermore, as depicted in Figure 6, among 54 Puerto Rican experts, 47 consider TEH to potentially enhance disaster victims' health and wellbeing, such as by reducing stress, anxiety, and/or depression, providing a sense of security and support, rebuilding self-esteem, and instilling hope. Moreover, the findings reveal that (1) approximately 52% of Puerto Rican experts, totaling twenty-eight individuals, consider origami shelters as an excellent solution for TEH post-disaster; (2) around 15% of experts, comprising four individuals, regard it as a very good solution; (3) approximately 28% of experts, totaling fifteen individuals, view it as a good solution; and (4) fewer than 6% of Puerto Rican experts, totaling three individuals, do not consider origami shelters to be a good solution for TEH post-disasters.

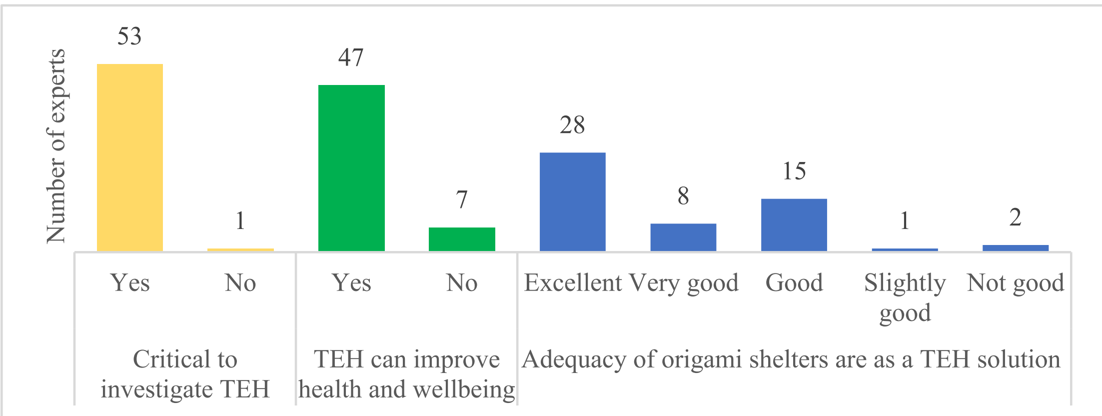

Figure 6. Experts' opinions related to TEH.

Low-income communities frequently reside in self-built informal settlements constructed without proper construction knowledge or skills, rendering them particularly vulnerable to natural disasters. Moreover, they encounter delays in post-disaster recovery efforts, resulting in improvised reconstruction endeavors that compound their vulnerability and exacerbate the housing and infrastructure crisis stemming from these events. Mindful of all this, the third section of the survey sought to understand the main challenges of informal construction and the potential benefits of providing education and training in construction trades and basic construction methods to low-income individuals. The results of this study, presented in box plots in Figure 7, highlight lack of structural knowledge, lack of quality control, inadequate construction methods, and lack of professional advice as the main problems of informal construction. Furthermore, according to the results of the study, 95% of Puerto Rican experts consider educating and training low-income individuals in construction trades and basic construction knowledge to facilitate more resilient post-disaster reconstruction, as shown in Figure 8.

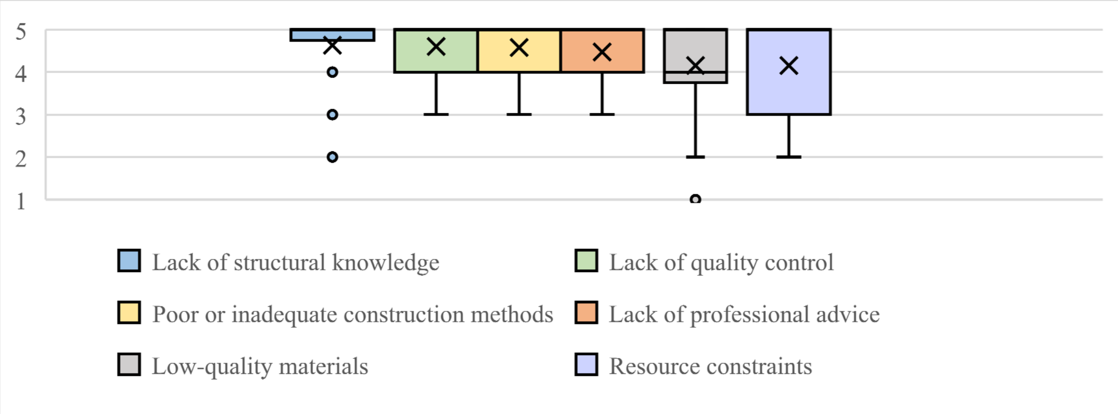

Figure 7. Main problems of informal construction.

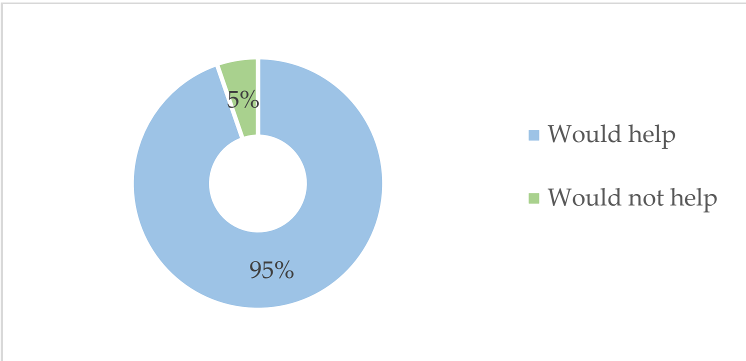

Figure 8. Experts' opinion on whether educating and training low-income individuals in construction trades would aid in more resilient post-disaster reconstruction.

Several courses related to construction trades and methods are deemed essential for educating and training low-income individuals to aid in more resilient post-disaster reconstruction according to experts' responses. These courses encompass carpentry, electrical, roofing, basic construction methods, and plumbing, as shown in Figure 9. Additionally, AEC professionals underscored the importance of additional courses such as basic structural knowledge, building regulations, sustainable construction practices, inspection procedures, foundation construction, material durability, and health and safety protocols, as well as heating, ventilation, and air conditioning (HVAC) systems. Moreover, experts identified teaching methods and instructional tools that should be employed to effectively educate and train low-income individuals. These teaching methods and instructional tools include (1) hands-on experience and on-the-job training, allowing individuals to gain practical knowledge through direct application rather than traditional classroom lectures or readings; and (2) problem-based learning, involving the resolution of real-world problems either independently or collaboratively. These results are presented in Figure 10.

The final open-ended question aimed to identify the recourses lacking in low-income communities. A word cloud, presented in Figure 11, was chosen as the visualization technique to effectively summarize and highlight the most frequently mentioned resources as indicated by Puerto Rican experts. As may be observed, the words 'knowledge', 'materials', and 'money' were the most frequently occurring, highlighting the importance of education and access to resources. Alongside these, other high-frequency terms such as 'education', 'resources', 'information', and 'construction' further emphasize the pressing need for adequate support systems. These collective data underscore the significance of education and knowledge in addressing the challenges and needs of these communities.

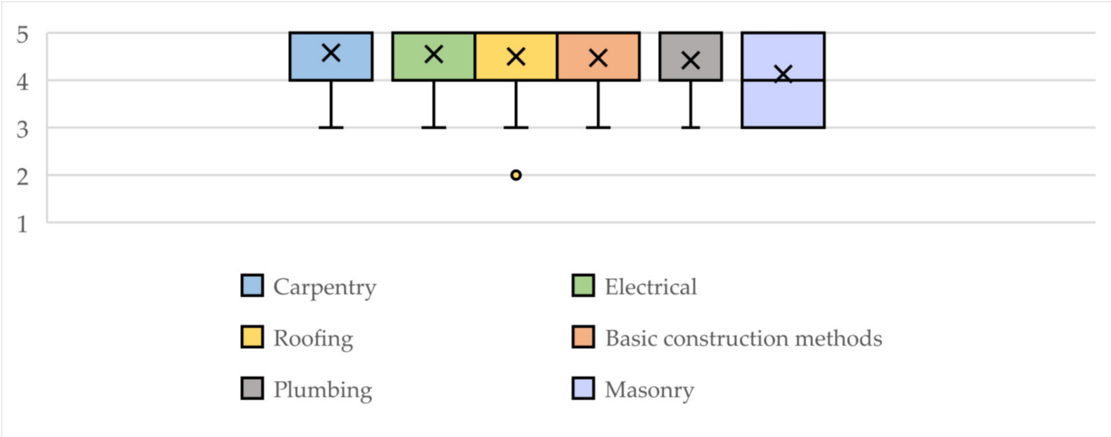

Figure 9. Essential courses for educating and training low-income individuals.

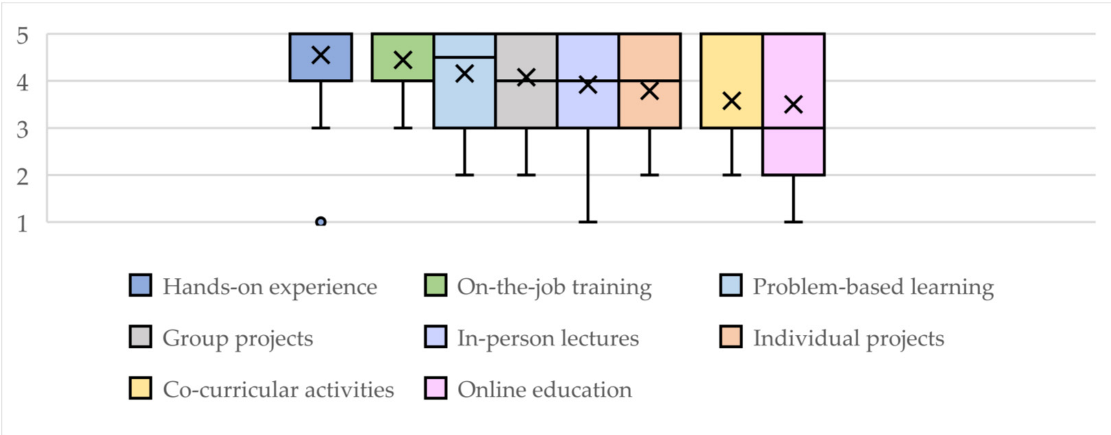

Figure 10. Effective teaching methods and instructional tools.

Figure 11. Lacking resources in low-income communities.

The authors employed several statistical measures, including KMO, Bartlett's test of sphericity, and Cronbach's alpha, within the SPSS 28 software to assess the consistency, reliability, and adequacy of the data sample size. The KMO value obtained was 0.639, surpassing the threshold of 0.6, thereby indicating adequate sample size. The calculated

Cronbach's alpha value was 0.859, exceeding 0.7, indicating the reliability of the sample size. The Bartlett's test of sphericity assessed the appropriateness of the correlation between variables. The obtained significance level was less than 0.001, signifying that the variables are not orthogonal.

Ordered Probit Regression Analysis

The ordered probit regression analysis addresses the second research question: What are the essential characteristics of TEH required to effectively address the major challenges, vulnerabilities, and crucial needs of low-income communities after a natural disaster, thereby aiding in quicker and more effective disaster recovery?

Table 1 depicts the outcomes of the ordered probit regression model evaluating the adequacy of origami shelters as a TEH solution post-disaster, exhibiting a Pseudo R2 value of 0.3673. Numerous variables have *p*-values of less than or equal to 0.05, indicating statistical significance. These variables include (1) the critical challenges and vulnerabilities that low-income communities face post-disaster, including lack of housing/shelter, lack of water and/or food, lack of electricity, health issues, mental health, and delayed disaster recovery; (2) the crucial needs of low-income communities post-disaster, including having a shelter, returning to work and routine activities, having water and food, having access to electricity, and emotional recovery; and (3) the key characteristics that TEH should have, including lightness, deployability, large production capacity, reusability, transferability, material sustainability, and easy disassembly. Thus, it can be inferred that the data support the hypothesis regarding the true relationship between the dependent variable, which is the adequacy of origami shelters as a solution for TEH post-disaster, and independent variables.

Table 1. Coefficients and *p*-value from ordered probit regression analysis.

Variables	Coeff. (β)	Std. Error	*p*-Value	Z
Lack of housing/shelter is a critical challenge	−2.59	0.95	0.006	−2.73
Lack of water and/or food is a critical challenge	−5.66	2.36	0.017	−2.40
Lack of electricity is a critical challenge	3.10	1.00	0.002	3.11
Feeling unsafe is a critical challenge	−0.44	0.97	0.651	−0.45
Health issues are a critical challenge	1.79	0.72	0.012	2.50
Mental health issues is a critical challenge	−2.76	0.96	0.004	−2.87
Delayed disaster recovery is a critical challenge	−4.16	1.75	0.018	−2.37
Having a shelter is a crucial need	4.58	2.21	0.038	2.07
Returning to work and routine activities is a crucial need	−2.52	1.17	0.031	−2.15
Having water and food is a crucial need	11.20	3.59	0.002	3.12
Having access to electricity is a crucial need	−3.69	1.50	0.014	−2.47
Emotional recovery is crucial need	2.79	1.26	0.027	2.22
Easy and quickly assembly is crucial for TEH	3.35	1.81	0.064	1.85
Being lightweight is a crucial feature for TEH	2.64	0.84	0.002	3.16
Readily availability is crucial for TEH	0.22	0.93	0.815	0.23
Deployability is crucial for TEH	−5.15	1.55	0.001	−3.32
Easy storage of units is crucial for TEH	0.58	0.81	0.472	0.72
Large production capacity is crucial for TEH	1.77	0.89	0.045	2.00
Reusability is crucial for TEH	3.09	1.13	0.006	2.74
Recyclability is crucial for TEH	0.58	0.84	0.491	0.69
Transferability is crucial for TEH	5.07	1.50	0.001	3.37
Using sustainable materials is crucial for TEH	−2.37	1.15	0.040	−2.06
Low environmental impact is crucial for TEH	−2.61	1.34	0.052	−1.95
Easy disassembly is crucial for TEH	−2.43	0.79	0.002	−3.07

Table 1. *Cont.*

Variables	Coeff. (β)	Std. Error	*p*-Value	Z
μ_1	3.91	2.99		
μ_2	4.18	2.94		
μ_3	5.88	2.87		
μ_4	6.55	2.88		
Number of observations			54	
Pseudo R-squared			0.3673	

In Table 1, μ_1, μ_2, μ_3, and μ_4 denote the coefficients of the ordered probit regression model, with values of 3.91, 4.18, 5.88, and 6.55, respectively. These values represent the thresholds reflecting the predicted cumulative probabilities at covariate values of zero. Based on the results of the regression analysis, several variables significantly contribute to the adequacy of origami shelters as a TEH solution post-disaster. These include (1) critical challenges such as lack of housing/shelter (β = −2.59), lack of water and food (β = −5.66), lack of electricity (β = 3.10), health issues (β = 1.79), mental health issues (β = −2.76), and delayed disaster recovery (β = −4.16); (2) crucial needs such as having a shelter post-disaster (β = 4.58), returning to work and routine activities (β = −2.52), having water and food (β = 11.20), having access to electricity (β = −3.69), and emotional recovery (β = 2.79); and (3) crucial features required in a TEH, such as lightness (β = 2.64), deployability (β = −5.15), high production capacity (β = 1.77), reusability (β = 3.09), transferability (β = 5.07), material sustainability (β = −2.37), and ease of disassembly (β = −2.43).

4. Limitations and Future Work

The authors acknowledge some limitations: (1) The survey responses might have been influenced by self-assessment and biases; (2) some participants may not have fully complete the survey as they tended to leave before finishing it; and (3) the research was solely carried out in Puerto Rico, potentially limiting the study's scalability. Nevertheless, this island faces high exposure and vulnerability to natural disasters due to its constrained financial resources, significant levels of poverty, and prevalence of informal construction. Furthermore, disaster recovery and relief efforts in Puerto Rico are slow and insufficient. Notably, 45% of Puerto Rico's population lives below the poverty line, and the island ranks among the top ten territories for economic losses relative to gross domestic product (GDP). This renders and reflects the sample as representative. Future studies could focus on conducting research in other regions to examine additional challenges, vulnerabilities, and critical needs that low-income communities face post-disaster, as well as the key characteristics required for TEH. Moreover, subsequent research endeavors could delve into strategies aimed at mitigating challenges related to the proposed origami shelters and evaluate the effectiveness of this solution through case studies conducted in diverse regions exposed to various types of natural disasters. Additionally, future studies could focus on the development of pedagogical approaches, encompassing courses, modules, seminars, workshops, teaching methods, and instructional tools aimed at effectively educating and training low-income individuals in construction trades. Drawing insights from existing construction trade programs available at different academic institutions could offer valuable guidance for these endeavors. These data could aid in post-disaster recovery and enhance the wellbeing of low-income communities. Furthermore, the data can help foster social mobility by enabling low-income individuals to access better job opportunities.

5. Conclusions

The results of this study underscore the importance of implementing sustainable, quick-assembly TEH as a short-term solution post-disaster. Temporary homes provide a means for disaster victims to better cope, offering a safe living environment and facilitating a sustainable return to normal activities while damaged infrastructure and homes undergo repair or reconstruction. As such, TEH can potentially improve the health and wellbeing of low-income individuals severely affected by natural disasters. In fact, 47 AEC experts agree that TEH can enhance the health and wellbeing of disaster victims. Furthermore, experts concur that it is critical to investigate TEH, with the proposed origami shelter highlighted being an excellent and effective TEH solution for addressing the housing crisis that arises or worsens in the aftermath of natural disasters. Specifically, 52% of Puerto Rican experts consider this an excellent solution, while 15% regard it as a very good solution.

The ordered probit regression analysis results shed light on the challenges and vulnerabilities faced by low-income communities post-disaster, outlining the key characteristics that a TEH should possess to serve as an optimal solution. These include addressing critical challenges and vulnerabilities such as lack of housing/shelter, access to water and food, access to electricity, health issues, mental health, and delated disaster recovery. Furthermore, the crucial needs of low-income communities post-disaster, including lack of shelter, the need to return to work and routine activities, access to water and food, access to electricity, and emotional recovery, are highlighted. Key characteristics that TEH should have include lightness, deployability, large production capacity, reusability, transferability, material sustainability, and easy disassembly.

Moreover, low-income communities often experience delayed disaster recovery, exacerbating the post-disaster housing and infrastructure crisis. According to this study's results, the recovery period for low-income communities following a major natural disaster, including repair and reconstruction efforts, can exceed one year. Consequently, natural disasters often lead to informal reconstruction efforts, where individuals rebuild their homes themselves in an attempt to recover from the disaster, inadvertently exposing themselves to great danger. AEC experts highlighted lack of structural knowledge, quality control issues, and inadequate construction methods as the main problems of informal construction.

Furthermore, the results of this research emphasize the importance of implementing a long-term solution, involving educating and training low-income individuals who are highly exposed and vulnerable to natural disasters in construction trades and methods. Additionally, the experts highlighted effective teaching methods and instructional tools for educating and training low-income individuals and underrepresented workforce. These methods include hands-on experience, on-the-job training, and problem-based learning.

The research findings indicate that low-income communities face two primary challenges: lack of housing and delayed disaster recovery. Access to housing is a basic human need, crucial for shelter, protection, and the overall wellbeing of individuals, families, and communities. Engaging in informal construction not only exposes individuals to housing damages and losses but also poses significant risks to their lives. Therefore, providing adequate TEH and equipping low-income individuals with construction skills will greatly enhance their overall wellbeing. Furthermore, offering training and education to low-income individuals not only assists in sustainable post-disaster infrastructure reconstruction but also fosters social mobility and job equity within our communities.

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