Direct Housing for Post-Disaster Recovery: Design and Logistics for Alternative Solutions

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ABSTRACT: *Considered a last resort in disaster recovery scenarios, direct-housing solutions are deployed only after other housing assistance options (such as rental assistance or temporary lodging) are exhausted. Their viability and effectiveness depend on a range of interrelated constraints, from unit costs to the logistics of storage, mobilization, and installation, and from their physical resilience to the seamlessness of their social integration. A particularly impactful constraint is the 18-month time limit placed on federal disaster housing assistance by the Stafford Act, which often results in abrupt and problematic transitions.*

In the United States, there is not a "one-size-fits-all" solution to post-disaster direct-housing systems, due to wide variations in disaster scenarios, logistical protocols, and the intent and timeline for the housing itself. Too often, the attributes that are desirable for direct temporary housing (speed and ease of delivery/setup, low labor and power requirements, etc.) are at odds with the durability, resiliency, energy performance, and even cultural expectations associated with permanent housing. Temporary MHUs of the past, such as those supplied by FEMA after Hurricane Katrina, are illustrative of these limitations. Alternative housing solutions that exhibit promising logistics attributes, such as rapid deployability, low cost, high modularity, etc., have potential to serve as adaptable solutions from temporary to permanent housing.

This paper presents in-progress research relating to alternative architectural solutions and production/delivery paradigms for flexible and adaptable post-disaster housing, ranging from volumetric modular to panelization to rapidly-assembled kit-of-parts systems. The paper concludes with a look at the current phase of this project, in which the effectiveness of recovery housing solutions is investigated through an integrated modeling and analysis framework for logistics planning and operations. This framework analyzes disaster housing solutions from a systematic perspective while drawing on converging research from multiple disciplines: architectural design, natural hazard and fragility analysis, and relief logistics network design and operations planning.

KEYWORDS: Disaster Recovery, Direct Housing, Adaptable

INTRODUCTION

In its 2016 report on the subject, the Congressional Budget Office (CBO) estimated that 1.2 million Americans live in locations at risk of substantial hurricane damage. It was stated at that time that hurricane damages cost government around $28 billion per year, and that this number will rise from the effects of climate change (Congressional Budget Office 2016). Newer data continues to speak to increasing severity of natural disasters and the urgency of this threat. According to the NOAA's National Centers for Environmental Information (NCEI), there were 18 separate billion-dollar weather and climate disasters across the United States within the 2022 calendar year, with hurricanes (including Fiona, Ian and Nicole) being the dominant source of destruction across the southeastern United States (NOAA 2023).

An interdisciplinary research team at Clemson University is currently in the midst of its third project in a series of studies relating to post-disaster relief and recovery. The work began in the 2018-19 academic year, as a team led by Industrial Engineering faculty and students developed a stochastic "look-ahead" approach for the optimization of hurricane relief logistics planning under uncertainty. The model aimed to minimize the total cost incurred in the logistics operations, which consist of transportation costs and social costs. That first study did not explicitly address housing, but focused on other relief materials. However, several key principles, including the notion of social deprivation costs for unmet demand, can be applied to direct-housing logistics. The second project in our sequence was aimed at studying a range of building solutions for post-disaster recovery, including direct-housing, which varied in their degree of prefabrication and in their methods of delivery and construction. These alternative design solutions and their associated data on costs, materials, dimensions, timetables, etc., would help provide case-studies for applying and testing an integrated housing design and logistics operations model, which is currently under development in the third project of our sequence. This paper will focus on the direct-housing design studies from project 2, and conclude with a look at the integrative modeling taking place in project 3. Throughout this work, our premise, which is supported by the background research summarized in the next section, has been that recovery structures should ideally exhibit the following attributes:

Flexibility: a flexible supply chain system that is adaptive to disasters of various types, locations, and severity is the key to support a successful deployment of medical and/or housing solutions during disaster relief, leveraging limited manufacturing, energy supply and infrastructure capacities.

Modularity: modularity in design solutions for disaster relief is a key factor to ensure that building materials are packaged, delivered, and assembled in affected areas in a timely fashion.

Reliability: reliability and resiliency of design solutions is the key to offering different levels of safety and durability under various disaster scenarios.

Adaptability: the adaptability of design solutions is the key to sustainable long-term disaster planning, allowing temporary structures, such as housing or medical facilities constructed immediately after a disaster, to be converted into more permanent houses later on.

1. BACKGROUND: DIRECT HOUSING

When natural disasters such as hurricanes strike in the U.S, states like South Carolina turn to their Emergency Management protocols, including their Disaster Housing Plans. The SC Disaster Housing Plan, which was last updated in 2018, states that: “The State of South Carolina must be prepared to ensure housing for those whose homes are not safe and sanitary due to a natural or man-made disaster.” (SCEMD 2018). Additionally, it identifies concerns of chief importance when it comes to locations of emergency housing, indicating that: “Key to the recovery of the State is individuals returning to their jobs and communities as quickly as possible after an event. A vital part of this rapid recovery is ensuring people remain as close to their homes and communities as possible.” The express purpose of the SC Disaster Housing Plan is to “identify available resources for locating, securing, and funding housing for people affected by a disaster within the State” (SCEMD 2018). When the resources of a local jurisdiction are exceeded, the State steps in to assist, and when the State’s resources are exceeded, the State can request federal assistance. This disaster management hierarchy and approach is common across the U.S.

When it comes to post-disaster housing, there are several stages of need which must be addressed. The first, which occurs in the immediate aftermath of a disaster is the need for Emergency Sheltering. Mass sheltering, if needed, is often accomplished in designated community buildings, such as school gymnasia, churches, etc., and is often supported by non-profits such as the American Red Cross or the Salvation Army. The next stage of housing need is Transitional Sheltering, which “consists of lodging that is not an emergency mass care situation, where each individual has their own access to the housing unit.” It requires a Presidential Disaster Declaration for the affected area. The Disaster Housing plan goes on to say that: “If Emergency Shelters are overwhelmed or FEMA determines shelter residents and evacuees cannot return to their homes for an extended period of time, the State may request FEMA authorize eligible disaster survivors to receive TSA (Transitional Shelter Assistance)” (SCEMD 2018). Transitional sheltering generally takes the form of hotel or motel rooms.

The next stage of need, if a need persists, is called Intermediate Housing. “Intermediate Housing consists of providing safe, sanitary, and functional conditions for individuals within a reasonable distance to schools, businesses, and services” (SCEMD 2018). Intermediate Housing is again dependent on a Presidential Disaster Declaration, and the housing solutions can take two different forms. The first is rental units located within or close to the affected area. The second, which is a last resort measure, is called Direct Housing. “If FEMA, in conjunction with the State, determines that there may not be a sufficient supply of available rental units to meet disaster housing needs, FEMA will survey those applying for Housing Assistance to determine if a Direct Housing mission is appropriate” (SCEMD 2018). The SC Disaster Housing Plan goes on to say that “direct housing can take many forms, depending on the needs of the affected communities and the resources available.” In seeming contradiction, it also states that “the only type of currently approved FEMA direct housing is factory made housing including mobile homes.” And, finally, the plan reports the following concerning the locations / placement of FEMA-provided Direct Housing:

> “The preferred method is to place housing units in locations where services and utilities are already established. This includes the placement of units on land owned by eligible applicants, and can also include utilizing existing manufactured housing parks and filling in vacant areas with disaster housing units given the appropriate infrastructure. This can be accomplished in as few as 24 hours and can remain operational for months. When those options are not available, or will not meet the needs of all affected people, FEMA may expand an existing mobile home park or create one to accommodate disaster housing” (SCEMD 2018).

The most well-known case of FEMA Direct Housing occurred in the aftermath of Hurricanes Katrina and Rita in 2005. In response to the devastation across the Gulf Coast Region, FEMA ultimately purchased 140,000 manufactured mobile homes and trailers for distribution. Shortly thereafter there were complaints about the construction of the homes, particularly the trailers. There were problems with formaldehyde levels from the off-gassing of the materials. The units also suffered from poor energy performance and a lack of durability and resiliency. It did not help that the transition to more permanent housing was complicated and delayed for many families. The FEMA trailers were never intended to be anything more than a temporary solution, but, in numerous cases, families lived in them for several years.

1.1 Flexible, expandable alternatives

In 2006, in conjunction with what it was learning after Hurricane Katrina, FEMA initiated the Alternative Housing Pilot Program (AHPP). It was aimed at identifying and evaluating better ways to directly house future disaster victims. Ultimately, FEMA provided over $400 million to four Gulf Coast states (Alabama, Mississippi, Louisiana, and Texas) to develop a range of recovery housing prototypes whose construction technologies were being advanced in the private sector. These solutions included site-built construction, panelized construction, and offsite modular and manufactured housing (FEMA/AHPP 2008). One of the common threads among early projects funded by the AHPP was "expandability", and the related notion of a temporary, deployed solution being adapted for long-term use. Such approaches have come to be referred to as "Temporary-to-Permanent" solutions. This idea is also reflected by concepts such as progressive shelters ("post disaster rapid household shelters planned and designed to be later upgraded to a more permanent status") and core shelters ("post disaster household shelters planned and designed as permanent dwellings, to be the part of future permanent housing"), as defined by the International Federation of Red Cross and Red Crescent Societies (IFRC/RCS 2013).

One particularly compelling example of a temporary-to-permanent post-disaster housing framework is the RAPIDO program developed by Building Community Workshop, a Texas-based non-profit community design center. Developed in the wake of Hurricane Dolly in 2008, the Rapid Disaster Recovery Housing Program (nicknamed RAPIDO), aims to create a "bottom-up community-based approach that is centered on the families it intends to support" (Building Community Workshop 2015). The RAPIDO direct-housing solution consists of a core dwelling unit intended for rapid deployment and occupation. This core unit is designed to be easily and incrementally expandable, so as to grow into a long-term house if desired. The goal is to help close the physical, infrastructural and policy-related gaps that often plague the transition from short-term recovery housing to long-term recovery housing.

The RAPIDO core includes one bedroom, one bathroom, a small kitchen and an open dining/living space. In total, it is approximately 480 ft2 in size (Building Community Workshop 2015). The unit is designed to be elevated above any flood waters, and its walls and lower roof are quickly assembled from prefabricated panels, each approximately 4ft by 10ft and constructed with in-line light wood framing. The panels include insulation, interior and exterior sheathing, and accessible raceways for electrical wiring. BC Workshop contracts with a network of different builders capable of providing these prefabricated panels. They are easy to erect and connect on site, which, in combination with the simplicity of the core unit design, makes for a fast and repeatable construction sequence. BC Workshop has been successful at finding funding and has been able to get numerous RAPIDO houses built, including in East Texas communities impacted by natural disasters.

Philosophically, the RAPIDO concept and its record of successful applications supports our team's key objectives of Flexibility, Modularity, Reliability and Adaptability. These objectives are further supported by the parameters of the Stafford Disaster Relief and Emergency Assistance Act, which was initially passed in 1988 and is regularly updated (FEMA 2021). The Stafford Act currently limits federal emergency housing assistance (including Direct Housing) to a duration of 18 months from the time it is first awarded. Thus, individuals or families receiving Direct Housing are required to transition out by 18 months. An alternative would be a private purchase of the house, or donation through a buy-back program. The possibilities for adapting and expanding the provided housing units make it more feasible that affected persons, and/or supportive non-profits, might elect to purchase the houses for permanent settlement. If the houses have initially been located on sites close to the pre-existing neighborhoods of the displaced victims, then this whole scenario can promote broader community resilience – everything from keeping individuals employed to keeping children in their schools to keeping key social networks (churches, community organizations, etc.) intact.

2. DESIGN STUDIES FOR NOVEL APPROACHES

Our design studies for disaster recovery structures followed closely from the background research described above in Section 1.1. Moreover, each of our studies prioritized the use of prefabricated wood building systems, for reasons of weight, constructability, flexibility and low carbon footprint, among others. On one end of the spectrum, we looked at modular units with varying degrees of offsite completion. Offsite volumetric modular construction holds the potential of being an especially fast solution for disaster recovery, particularly if units are built and stored in advance of disaster events as in the case of FEMA's standard approach. While fast to deploy, the modular approach does carry the most intensive demands for transportation and installation, in that it requires heavy moving equipment at all points between the factory and the building site. This approach also demands the greatest amount of space and volume for pre-deployment storage, supposing that units are planned and prepared in advance of a disaster.

On the other end of the spectrum, we studied an approach that would utilize a kit-of-parts system in which prefabricated components could ship in a condensed format (flat-packed on palettes, for example) and then be assembled on site. For this, we turned to a unique light framing system which has been under development at Clemson University since 2014. Compared with offsite-fabricated modular units, a kit-of-parts approach is necessarily more intensive and time consuming when it comes to onsite installation, though design measures can be taken to make assembly of the components easy and safe, like a puzzle, making it favorable for situations in which volunteer and/or low-skill laborers are in ready supply. This approach is also nimble to prepare, store and deploy, and could be useful for sites which may be hard to reach with tractor trailers. Each of the two methods (Modular and Kit-of-Parts) is summarized in the following sections, with the designs for core units and their expansions being illustrated therein.

In the middle, between the offsite modular approach and the kit-of-parts approach, is the panelized construction approach, utilizing some combinations of prefabricated wall, floor and roof panels, as exemplified by the RAPIDO concept from BC Workshop. RAPIDO, whose closed-panel, light wood construction supports reasonably fast project delivery and installation, and whose clever detailing, including accessible raceways for wiring, supports flexibility and expandability, has served as our consistent reference point for a panelized design.

2.1 Volumetric modular units

Supported through a grant from the USDA, and in partnership with the U.S. Forest Products Laboratory, our team's work on volumetric modular designs, actually began by studying the topic of deployable medical relief units for the rapid delivery of medical supplies and clinical care to areas whose hospital systems may be overwhelmed or out of reach. The premise was that these structures could be designed to be adaptable into housing units for use during the subsequent recovery phases. While this part of our study is not the subject of this present paper, it is worth noting that our research led us to the precedent of deployable medical modules from *Clinic in a Can*, a non-profit based in Kansas who retrofits steel shipping containers for use as off-grid-capable medical relief units (Clinic in a Can 2023).

With this example in mind, and considering the ease of transportation and the widespread familiarity with standard shipping container sizes, we elected to stay with ISO container dimensions as a parameter. Standard containers come in 20ft and 40ft lengths and are 8ft wide by 8'-6" tall. "High Cube" containers, which are also quite common, are a little bigger in cross-section at 8ft wide and 9'-6" tall. The additional ceiling height drove our team to utilize the "High Cube" dimensions for our basic modular unit. As in the example from *Clinic in a Can*, we considered the 20ft unit length to be the most versatile and nimble, and the majority of our work focused on this size. As an alternative to steel containers (whether new or recycled), our team based its designs for the 20ft x 8ft x 9.5ft modules on the use of mass timber panels, specifically cross-laminated timber (CLT) for a variety of reasons. These included: the natural insulating qualities of timber; the flat surfaces of CLT which enable the use of standard format rigid insulation; the fact that CLT presents a continuous structural substrate for mounting or attaching without blocking; the rigidity of the panels themselves which negates the need for space-consuming moment-framing; the ease of window and door openings without a need for engineered framing; the ability to expose the CLT as a finished surface; the fact that wood is a renewable, carbon-sequestering material; and the potential for reclaiming and reusing entire panels in the event the modular units are decommissioned or highly altered in the future.

For the potential of shipping supplies (medical or otherwise) in the units themselves, we considered one end wall of the unit to be open (or openable), just like a shipping container. Next, we located a single door within a larger opening in one side wall whose dimensions would match the unit's end opening, enabling two units to join in a T-shaped configuration, if desired. This is the sort of consideration that reflects the project goals of Modularity and Adaptability. The door and transom in the side opening would be installed within light framing used to infill the larger rough opening in the CLT. Similarly, the wall that infills the end-opening, plus any interior partition walls would be of light framing. This framing and finishing could be completed offsite by the modular manufacturer, or could be completed onsite after the units are placed, whether by stick framing or through the use of prefabricated infill panels that ship with the unit. Operable windows would be located in rough openings across from the single doors in order to enable cross-ventilation.

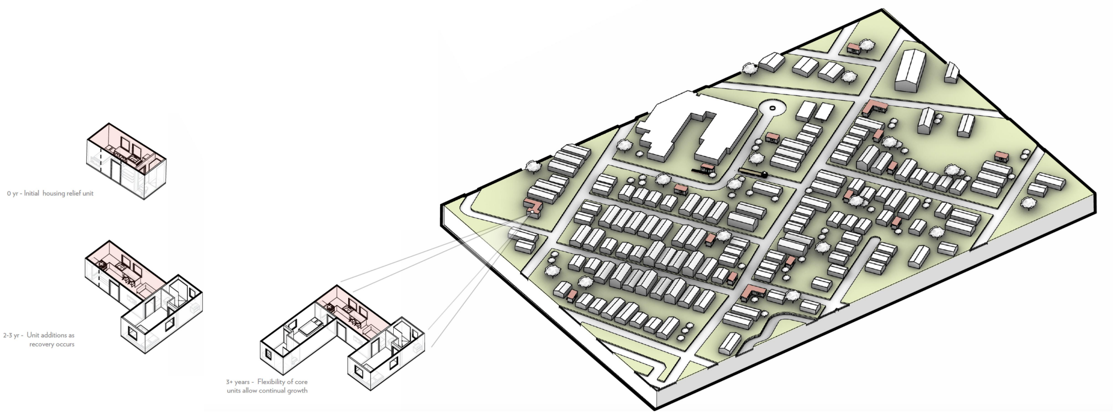


Figure 1: Core unit and expansion scenarios visualized within flood-prone Charleston, SC neighborhood. Illustration by: (Ryan Bing 2021)

From a structural standpoint, it was imperative that the timber units be able to be moved and stacked just like steel containers. With this in mind, our partners in Civil Engineering designed for the rigors of lifting and transporting, while even planning for payloads of medical supplies or units of blood. Using SPF V2M1.1 panels from Stucturlam (a manufacturer based in British Columbia) as the initial basis of design for the CLT, the team concluded that 3-ply panels would be sufficient for walls, floor and roof. Later the team looked at 3-ply, Southern Pine SL-V3 panels from SmartLam's factory in Alabama and drew the same conclusions. Outer laminations would run vertically in the wall panels, and would span in the short direction for roofs and floors. Structural analysis confirmed that the desired sizes and locations of the rough openings would be permissible.

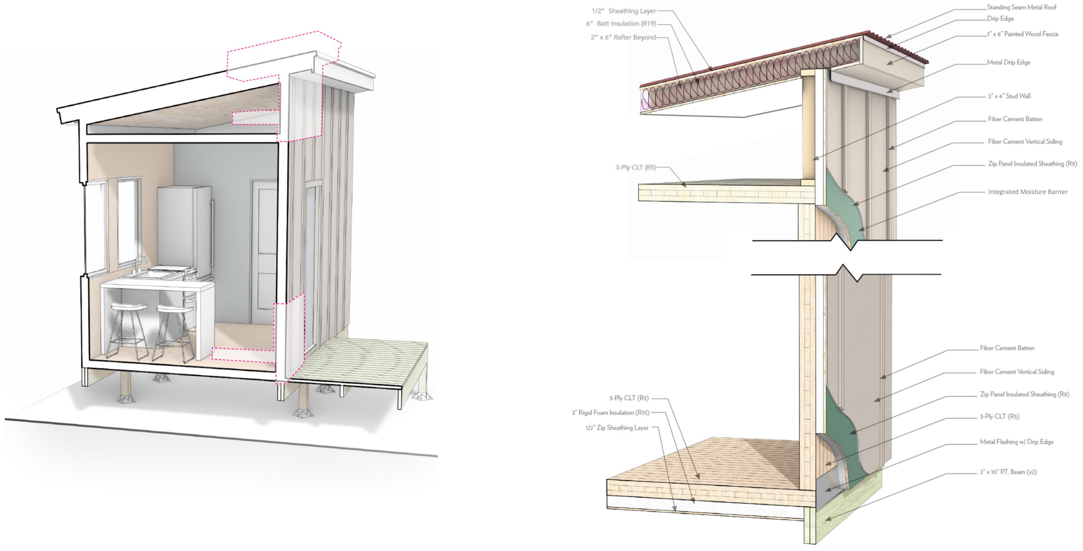


Figure 2: Cross-sections depicting unit finishes and on-site completion measures. Illustration by: (Ryan Bing 2021)

The units could either be shipped with a house-wrap preinstalled, later to receive rigid exterior insulation and finishes, or with a disposable weather-proof wrap, later to receive an insulated sheathing panel with integrated moisture barrier (and taped seams), plus finishes (e.g., Fig 2). Once onsite, units would be installed atop a raised substructure and reversible pin footings, offering resiliency, ventilation, and reusable foundation components. Other onsite work would include a pitched roof, which could be stick-built or assembled from prefab, light-wood framed panels. Roof designs could be tailored to suit the surrounding context or occupant preferences. Mechanical heating and cooling needs would be addressed by the inclusion of a multi-zone ductless mini-split system. These systems are compact and efficient, requiring only a small outdoor heat exchanger and wall-mounted interior units placed as needed. Like the examples from *Clinic in a Can*, the units could be powered by diesel generators, or, ideally, by integrated PV panels and onboard batteries for energy collection and storage. The ability to operate independently from the power grid is an important post-disaster consideration.

2.2 Kit-of-parts units

As an example kit-of-parts approach, our team turned to the “Sim[PLY]” framing system, which was first developed and utilized for Clemson’s entry in the 2015 Solar Decathlon Competition, and has been refined through several iterations and applications since. This system utilizes CNC-milled ¾”-thick plywood components which fit together like a puzzle and rely on a combination of unique wood-to-wood joints. It leverages the speed and accuracy of prefabrication for on-site assembly that is intuitive, safe, and quiet, without the need for heavy construction equipment, saws, nail guns, or other power tools. Walls, floors and roofs consist of built-up members (serving as studs, joists, and rafters/trusses, respectively), each featuring a plywood web and two plywood flanges (interior and exterior), and resulting in highly-insulated cavities. The flanges serve as strips through which to screw structural sheathing and interior finishes. Flanges and webs are joined by wood-to-wood tab and slot connections and secured by steel cable ties. Stud, joist and rafter webs are designed and milled for the rapid and integrated passage of MEP services.

During its development, the system’s structural performance has been tested through a series of coordinated ASTM test procedures. There were single-fastener tests to understand shear strength of the tab and slot joints, others to test screw withdrawal from the plywood flanges, and others to understand the tensile capacity of the cable ties. Full scale tests were performed on roof rafters (to test bending strength) and also on 8ftx8ft shear walls (to test racking strength and resistance to lateral deflections). Ultimately, the system was shown to be suitable for expected gravity loads and also suitable for seismic category D2 and wind speeds of up to 135mph.

In addition to its ease of assembly, the Sim[PLY] system is likewise easy to disassemble non-destructively. Once the steel cable ties are cut, the joints are reversible and pieces can be replaced or reconfigured. Using this logic, the frame can be designed with features that support the notion of adaptable and expandable structures. For example, door and window openings are designed to be interchangeable through the use of a removable sill and the joints in the studs that support these sills. Similarly, rafter components can be designed and milled with joints that accommodate future rafter extensions for roof additions.

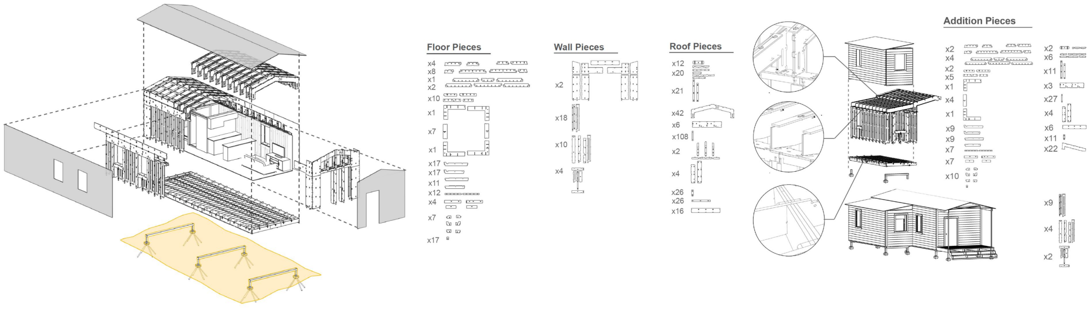


Figure 3: Core unit and bedroom addition utilizing Sim[PLY] framing system. Illustration by: (Daniel Mecca 2021)

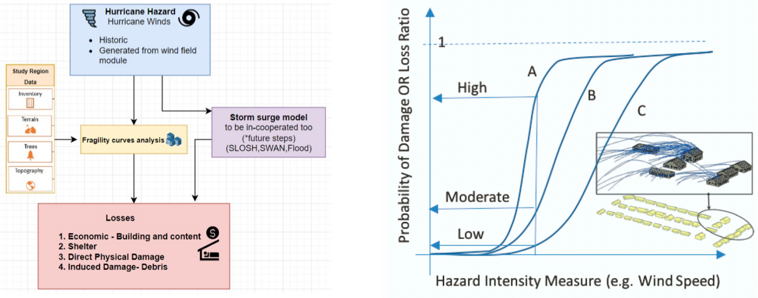
As a starting point, and for the purpose of future comparison, the layout of the kit-of-parts core unit was designed in reference to BC Workshop’s 1-bed, 1-bath RAPIDO CORE. An optional 1-bed addition was also designed. The framing would be sheathed using structural sheathing with an integrated moisture barrier. Exterior cladding and interior finishes could be anything that the budget and conditions warrant, but systems that could be easily disassembled and reused would be ideal in the event that the housing units are eventually recovered and repurposed. For the interior of the housing unit there is the potential to use prefabricated bath and kitchen assemblies with a shared wet-wall, something we are still researching. This would provide a fast and integrated installation. Alternatively, the restroom walls (including the shared wet-wall) could be framed on site using Sim[PLY] components or conventional framing, and then plumbed and wired. Like the CLT modular solution (see Section 2.1), the Sim[PLY] solution utilizes an elevated undercarriage of beams (built-up from dimension lumber) and prefab pin footings. The porch and steps are likewise framed onsite.

3. INTEGRATED DESIGN AND LOGISTICS MODELING

The third and current project in our sequence is being supported by NSF’s Disaster Resiliency Research Grants (DRRG) Program. Building upon the earlier logistics modeling from project 1, the main objective is to create an integrated modeling and analysis framework for disaster housing designs and logistics planning, including evaluating and enhancing their effectiveness in resilient hurricane response and recovery. The framework will integrate the physical resilience of disaster housing, the system resilience of the disaster housing supply chain and logistics network, and the operational resilience of robust and adaptive logistics operations under various hurricane scenarios. The team aims to analyze recovery housing solutions from a systematic perspective while drawing on converging research efforts from multiple disciplines: natural hazard and fragility analysis (in service of prefiguring demand for direct housing); relief logistics network design and operations planning (in service of identifying supply); and architectural design. This work is ongoing, but the basic elements of each of these threads is described below.

3.1 Demand for Direct Housing Assistance

Three modules have been developed to estimate the housing assistance demand scenarios. Module One, the hurricane hazard module, quantifies hurricane hazards on a study domain (e.g. South Carolina) using simulated hurricane tracks based on historical observations. This study uses a stochastic simulation framework, which consists of several modules including a hurricane formation model, tracking model, intensity model, central pressure filling rate model, and wind field model. Module Two, the loss estimation module (e.g., Fig 4a), analyzes the hurricane hazard in order to calculate housing damage and monetary loss. The damage includes downtime for each building in the hurricane-affected region. Module 3, a fragility framework was developed to apply the risk to various residential buildings within the hurricane zone (e.g., Fig 4b). The study region data is taken from the FEMA inventory, which draws from the 2020 US census and the Nationwide Structure Inventory (NSI). The inventory includes data of the study domain such as tree parameters, building counts, populations, and building exposure values. Building fragility curves are used to predict damage and loss of residential buildings according to wind building classes (e.g. one-story wood building or multi-story apartment). Future work will integrate the three modules. The actual observed losses will be compared with the loss estimation results and the estimation framework will be recalibrated as necessary.



Figures 4a and 4b: Framework for hurricane hazard loss and damage estimates. Source: (Authors 2023) and Example damage fragility curves. Source: (Grayson et al. 2013)

3.2 Supply of direct housing assistance

The team is proposing an optimization model to capture the logistics process for transitional housing after a disaster. The model aims to address the logistical planning challenges brought by the gap between estimation and actual data. A regression-based forecasting model for the housing demand estimation has been created and is being calibrated using historical hurricane data and socioeconomic data. A two-stage optimization model has been built to capture the short-term logistics plan and address the housing demand uncertainty (e.g., Fig 5). The first stage corresponds to the preparation of disaster housing supplies prior to the realization of the housing demand, and the second stage corresponds to the operational decision making to address the housing demand that has been realized. To account for the extreme scenario of unexpectedly high demand, we consider two modalities for the operational decisions: a typical supply plan (based on the first-stage preparation only) and an emergency supply plan (which includes "emergency acquisition" decisions).

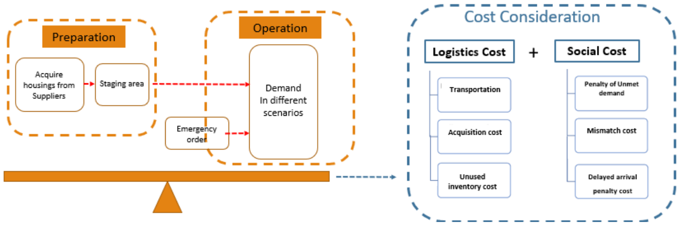


Figure 5: "Two stage optimization model" is the short-term logistics plan and cost consideration. Source: (Authors 2023)

3.3 Architectural designs as inputs

Drawing on case-studies (such as BC Workshop's RAPIDO) and on the unit designs described in section 2, we aim to examine a set of alternative direct-housing designs across a range of prefabrication and delivery scenarios, all to address common needs and logistical concerns associated with post-disaster housing. This includes: cost of materials; logistics of storage and transport; speed of production and delivery; speed and ease of installation; required labor force; space, equipment and power required for on-site construction;

structural resiliency; and ease of adaptability and expandability. Data associated with this list of attributes, plus any others deemed important, will be coordinated with the hazard analysis and plugged into the optimization modeling described above. To date, we have gathered data on the conventional FEMA MHUs and trailers deployed after Hurricane Harvey in 2017. This serves as a baseline case and as an aid to refining the optimization model. Data for the RAPIDO unit (representing a panelized approach from a network of builders) has been obtained through communications with BC Workshop and through published reports, including the 2020 Disaster Recovery Alternative Housing Study commissioned by the Texas General Land Office (Hagerty Consulting 2020) – a study which again affirms the desire for “temp-to-perm” solutions.

Detailed fabrication costs and timelines on the Sim[PLY] framing system have been gathered over the course of past building projects, but will need updating for our proposed kit-of-parts recovery unit. The material costs for the plywood frame are tracked using the known sheet count derived from our nested cut files. Final decisions still need to be made on the sourcing of the interior elements. Finally, the team will decide whether to move forward with mass timber modular units. Up until this point, meaningful production data has been elusive because of a lack of modular builders working at the intersection of mass timber and affordable, single-family units. However, we very recently learned about the Hacienda Community Development Corporation in Oregon whose *Mass Casita* housing program seems to check each of these boxes, and we are hopeful that this provides an avenue for data collection and inclusion in our optimization modeling (Hacienda 2023).

CONCLUSION

This work is very much in-progress, with the synthesizing of our studies happening in the third and current project. We aim to test a range of different housing designs and construction/delivery methods, as characterized by the examples presented in this paper. The solutions will be tectonically and operationally different, but will share the objectives of Flexibility, Modularity (at different scales), Reliability and Adaptability/Expansion to address logistical and policy constraints. The research will create novel stochastic optimization models and solution approaches that will help improve disaster housing logistics network design and operations for SCEMD and beyond, and may result in myriad, blended solutions depending on the specifics of a given disaster scenario. We look forward to publishing our full results in the future.

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