Volumetric Construction: Learning from Sweden, Finland, and the United States.

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Fig. 1. Volumetric Construction, Lulea, Sweden 2024. Image by Author.

Abstract

The global affordable housing crisis is escalating. In the United States, particularly in the Midwest, the apparent abundance of housing belies a stark reality. Individuals of all ages with modest incomes and full employment struggle to secure safe and affordable housing. To enhance availability and access, it is imperative to innovate and reduce production costs while increasing the construction of housing units.

The 2023 housing profile for the State of Indiana, compiled from data by the National Low Income Housing Coalition and published by state senators, underscores a severe shortage of affordable housing. The state requires an additional 120,000 units to meet demand. Only 39 out of every 100 extremely low-income individuals have access to affordable housing[1]. This issue is pervasive across the United States, compounded by a 60% increase in residential property prices since 2000.[2]

Introduction

This paper presents the findings from our research on volumetric construction, including field visits to major factory-built housing companies in Sweden, Finland, and the United States. These visits aimed to address the principal research question: Is volumetric construction a viable solution to the current housing shortage?

Our research methodology involved interviews with industry architects, designers, factory engineers, and managers specializing in urban manufactured housing development. We focused on the integrated practice model required by volumetric production. Data was collected through tours of advanced contemporary factories, which increasingly utilize automation and robotics. We identified limitations and special design considerations necessary for efficient production. It became evident that architecture and architects must adapt their design strategies to fully leverage the benefits of factory-built structures. In this context, architecture, design, and construction transition from service provision to product design, necessitating the development of new workflows and techniques.

We catalog and present our findings, discussing the systems, construction methods, and technologies employed in significant factories in the U.S. and Sweden. We also propose conceptual recommendations for future public-private partnerships to address and potentially ameliorate the current affordable housing shortage.

Our growing housing crisis

The 2023 Indiana housing profile, based on data from the National Low Income Housing Coalition, indicates that there are 199,050 extremely low-income (ELI) renter households in the state. During this period, there was a shortage of 120,796 rental homes available for this population. Households with an annual income of $26,500 or less for a four-person household are classified as extremely low-income (ELI) households. In 2023, a household in Indiana required an annual income of $35,299 to afford a two-bedroom rental home at HUD's Fair Market Rent.

Seventy-one percent of ELI households are also cost-burdened[3], meaning they allocate more than 28% of their income to housing costs. In many cases, this burden exceeds 50% of their income. Additionally, households of color are more likely than white households to be renters and have extremely low incomes. It is also important to note that housing access may exist in towns and cities distant from areas of greatest need.

This situation is further complicated by recent outmigration from several major metropolitan areas, including New York City, Boston, Washington, Chicago, Los Angeles, and San Francisco[4], initially triggered by the 2019 pandemic. This migration has somewhat benefited smaller and mid-sized cities like Indianapolis but has also indirectly exacerbated the housing crisis. A substantial infusion of new multi-family structures is required in growing locales. In Indiana alone, the need exceeds 200,000 units and is expanding. Housing access remains critically low, and the market currently lacks the capacity to address this challenge. A consistent and systematic approach is essential to mitigate this problem, necessitating increased production within a compressed timeframe.

Fig. 2. Out migration from major urban centers. Source Freddie Mac Loan Product Advisor ®.

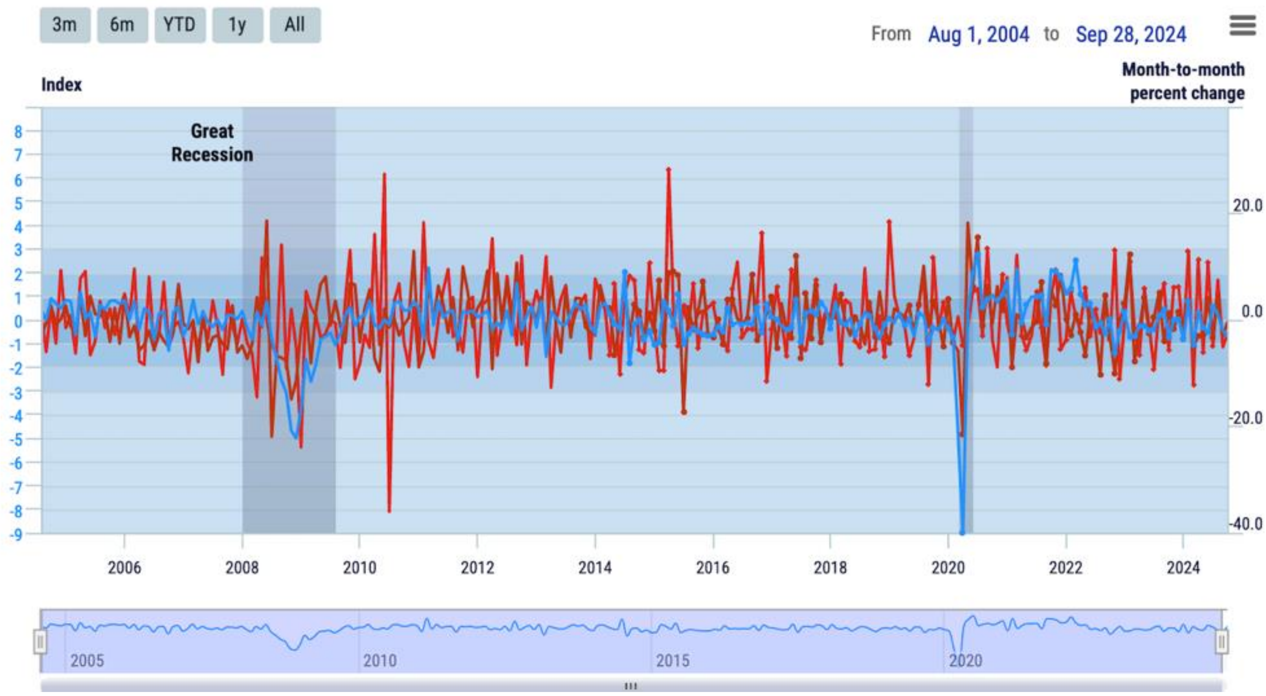

Fig. 3. From August 1 to September 28, 2024, the Census Bureau reports a -3.1% in multifamily housing permits and a -5.1 in housing unit completion nationwide. The aggregate index is nearly half a point down. The 2020 drastic housing dip is also apparent. Source: U.S. Census Bureau Economic Briefing Room (Census.gov).

The young and the elderly with single or fixed incomes are excluded from the privilege of living in quality, affordable housing.

Many existing subdivisions and platted neighborhoods prohibit their introduction through existing codes, regulatory limits, and covenants.

Volumetric building process summary

Historical Perceptions

The adoption of manufactured homes faces challenges due to historical perceptions of inferior quality, leading to prohibitions in many subdivisions and neighborhoods.

Fig. 4. Lindbäcks, wall construction beds, Image by author, 2014.

Volumetric residential mid-rise buildings

The focus is on urban multi-story, multi-family buildings, typically ranging from two to eight stories. Buildings above six stories also require a timber frame. Each volume is approximately 35 m² with ceiling heights of 2.5 m. For instance, a five-story project in Stockholm by Lindbäcks included 95 volumes and was completed in two weeks. These buildings feature high-quality materials, contemporary amenities, and allow for architectural expression and personalization. They are constructed by stacking fully finished volumes.

Structural Design and Onsite Work

Volumes are designed to handle the loads and stresses of multi-story buildings. Onsite work, including foundations, is initiated simultaneously with the start of factory production. Completed volumes are transported and stacked using cranes. This integrated process reduces waste, improves quality, and shortens time to occupancy. Building codes and inspections are performed in bulk at the factory floor, unlike the often-delayed stick-built projects.

Operational advantages

Labor availability is consistent and stable, unaffected by weather or natural events. Theoretically, the production line can operate safely and continuously using multiple shifts 24/7, drastically improving efficiencies and shortening overall project delivery.

Redesign for Modularity

Designers must create interest and functionality through patterns, integrating spatial and technical knowledge. Minimizing on-site interventions is desirable, with as much work as possible done at the factory. Volumetric packages, such as bathrooms and kitchens, are often produced at sister factories and inserted into the volume. Project material supplies are procured pre-cut to exact dimensions. Material kits are positioned respectively to feed production lines continuously.

Architectural Collaboration and modular design

Successful volumetric projects require training and coordination between architects, developers, and the factory. Factories may also offer independent interface services to assist with modular design adaptation. Architectural designs must conform to specific fabrication strategies, with module repetition being preferable. Once a production scheme is finalized, a team processes the necessary code for machining each part with high accuracy.

Fig. 5. Packaged Bathroom systems. Image by Author. 2024

G-codes production

A specialized digital technology group translates the designers' plans into machine language (g-code) before factory lines start. Once this preparation is complete, machines are programmed, and production begins. Exact tolerances must be strictly respected.

Product Run

All line teams meet to overview the run and address potential concerns. Once all managers agree, the run is initiated. Minor modifications may be implemented as innovations are discovered. This pre-run integration is sometimes absent in stick-built construction.

The Swedish experience

In Sweden, integration starts with sustainable forest harvesting as well as waste reprocessing. Labor safety and employee fulfillment are essential core values.

Lindbäcks and BoKlok are the country's two major volumetric producers. Lindbäcks operates an advanced factory in Haraholmen aiming to produce one apartment (two volumes) every hour. At Haraholmen, teams meet daily to discuss the upcoming factory run, with a focus on teamwork and safety. Facilities include a workout room, meeting rooms, and a cafeteria. Hiring is not reliant on previous construction experience, with team members trained by the factory. Tasks are made more convenient, with walls constructed on horizontal mechanical beds that can turn and flip, simplifying framing, electrification, plumbing, and finishing.

Worker safety is paramount. The factory produces 16 volumes per day. The factory employs 150 co-workers, with all instructions and drawings on the factory floor are available on demand only in digital form.

Error and incident reporting

The factory has a reporting whiteboard on the factory floor dedicated to line efficiency, errors, and incidents, which are discussed to improve coordination. Both quality and speed are valued, with a focus on production line-flow avoiding production bottlenecks. One completely manual production segment, set in between two automated ones, has never caused jamming or work stoppage.

Exterior Finishes

After stack installation, exterior finishes, balconies, and accessories are added onsite, providing more choice and superior quality. This process unifies the architectural façades and visually connects the stacked volumes.

Finland

PLUS PUU in Finland offers a log home construction system for single-family homes. This concept differs from volumetric building and is commonly used for single-family homes. Units arrive as prefabricated kits with precision and accuracy. The logs' geometry provides structural stability, two integrated gaskets installed between each log practically eliminate infiltration, sealing the system from both water and air. These structures perform well in the harsh Finnish winter due to their tightness and craftsmanship. The logs are made from either spruce or pine. Spruce offers a more consistent and lighter clear color, while pine varies drastically due to the oils in the wood. Although no additional insulation is typically added to the walls, there is 30 cm of rigid

Fig.6. Lindbäcks at Haraholmen, Sweden, main factory floor. Image by Author 2024.

Fig. 7. PLUS PUU Log systems. Examples of both birch and pine woods. Image by Author. 2024

insulation under the slab and 50 cm of mineral batt insulation for the roof.

Logs can be as long as 12 meters (39.3 ft) and are made from laminated timber. The top advantages listed by PLUS PUU include non-settling logs, fast assembly, no post-construction adjustment, the main material being also the interior finish, no glues, healthy indoor air quality, and ecological responsibility. Just like volumetric building, foundation and other site work are initiated as the factory produces the home. Logs may be shipped in containers and arrive at the site with a PLUS PUU specialized construction team to assemble and erect the kit.

PLUS PUU also extends its services to North America, offering fast assembly, and ecological responsibility.

U.S. Operations

In the United States, three types of operations were observed, often informed by transplanted Swedish executives and experts. These operations vary in their level of adoption of digital technology and automation in the manufacturing process. These may be cataloged in the following three categories:

I - Stick-built under roof

These factories build volumes using traditional nail guns and hammers, like a conventional job site, but within an environmentally controlled space. Production efficiency is enhanced by the setup, in-place power equipment, cranes, and lifts. One such operation in our home state demonstrates significant economic advantages over traditional stick-built projects.

II - Highly automated factories

Some U.S. factories have successfully implemented high-level automation. For example, Autovol in Nampa, Idaho, operates a factory resembling a contemporary automobile manufacturer, with robot arms laying, cutting, and installing building systems. They refer to their process as "automated volumetric construction," aiming to reduce time, labor, and improve quality. Autovol has built nearly three thousand apartments, totaling 2.3 million square feet, and is in high demand, particularly in California. They are sought after by mayors and municipalities to help grow local housing stocks.

III - Hybrid-factories Automation with skill labor integration.

Hybrid factories combine automation with traditional stick-building techniques. These factories, like those of Lindbäcks's, use machines to simplify construction while still relying on skilled labor. Co-workers are involved in all aspects of production.

Product more than Service

An Autovol, officer, referring to volumetric construction, said, "We are now producing a product, not providing a service." This shift involves different laws and standards, with research, replication, and innovation improving quality while reducing costs and environmental impacts. Material waste is minimized and can be reintroduced into the production system. Volume buying and shortened construction time optimize costs, while automation enhances consistency, quality, and safety.

Volumetric Building in Education

Despite its potential, volumetric construction is not widely taught in architecture schools. Modular design has historical precedents, such as the Sears Roebucks kit homes from 1908 to 1940. Although, many schools have digital fabrication programs, the study of volumetric construction is often overlooked. The field is expanding globally, producing hotels, hospitals, and residential projects. The required knowledge base includes industrial engineering, product design, architecture, digital fabrication, structural, mechanical engineering, and material science. Material science is critical for this mode of construction. Traditional construction materials, such as gypsum board for walls and ceilings present challenges for producers. These materials are brittle and sensitive, not performing well in transportation and erection. Repair teams are often sent to the site to remedy potential cracks and imperfections. We need to rethink volumetric design, treating it more as a product design and develop new materials and processes more conducive to forming and constructing these units. New ideas, systems, materials, and processes are needed, representing rich opportunities for academic research institutions, programs, faculty, and students.

The Case for Public Private Partnerships

Volumetric construction offers a compelling and convincing case, but challenges persist, particularly the substantial capital required for initial setup. For instance, the Haraholmen factory in Sweden projected a budget of $48 million in 2018. Furthermore, financing individual volumetric projects is equally challenging in the U.S., as financial institutions are resistant to approving upfront financing before onsite construction begins. Volumetric factories necessitate advanced funding to purchase large amounts of stock material, timber, finishes, and appliances before production starts. Owners and developers face resistance from financial institutions due to the evolving nature of this updated construction mode.

Furthermore, not all sites are conducive to volumetric construction. Some localities prohibit their inclusion either by zoning laws or neighborhood covenants[5]. Although attitudes are fast changing, public-private partnership policies and systems are needed to further establish and promote the development of volumetric building. Such a strategy would be an extremely beneficial and desirable tool to address the growing housing crisis. Here, government can play a pivotal role in facilitating the creation of volumetric operations that can create jobs, develop new sectors of the economy, while also providing housing access to all segments of our communities. The public sector can be an effective catalyst through various available tools, including incentives, tax rebates, land banks, and other potential assistance. This can be initiated at federal, state, or local levels.

An interesting private-public sector model is the development of Factory_OS. Located in an old navy submarine facility in the Bay Area of San Francisco, this organization is growing due to strong partnerships with local corporations such as Citi, Autodesk, Google and Facebook.[6] These businesses support Factory_OS due to San Francisco's challenging housing market. They have proactively ordered several housing projects, with funding coming directly from them. Multiple housing projects are being constructed to benefit both their own respective workforces and the community at large. The business models can vary, but the future of this industry is bright and growing. Our universities and architectural programs should take note.

Conclusions

We are amid a dramatic and worsening affordable housing crisis. Both young adults with jobs and retired seniors on fixed incomes are finding it hard to access affordable housing. Volumetric design and construction offer a new process to meet this challenge. This mode of construction features many advantages, including construction cost savings, but more importantly, it dramatically shortens the construction period, which in turn improves overall project development costs and can address severe shortages in less time. Factory-built homes arguably also have superior build quality. Structures are constructed in roofed, environmentally controlled spaces that offer protection from inclement weather and provide improved workforce safety. In fact, Sweden uses offsite manufacturing to build at least 45% of its new homes.[7] In Sweden, higher emphasis is placed on protecting jobs and the quality of workers' engagement in operational decisions. Automation there has not significantly impacted labor force reduction. Consequently, savings are mostly through increased production capacity, shortening project schedules and financing periods, resulting in significant savings in development costs.

In contrast, the U.S., has a few emerging operations heavily reliant on robotics and automation, promising even more savings in construction costs, production time, and overall development costs. While the industry and municipalities have not yet adapted to this important technological evolution. Many aspects of construction laws, regulations, zoning and covenant restrictions, financing, training, and education need to catch up with its development. This industry is on the cusp of major escalation in adoption, acceptance, and implementation. For widespread implementation, commitment and investment from both the public and private sectors are essential. In the U.S., a detailed plan is necessary to further integrate and familiarize communities with this potentially transformative solution and construction method. Currently, major corporations such as Google and Facebook are teaming with West Coast producers to support their operations and improve the housing market in their area. A public-private collaboration will assist communities experiencing housing shortages to replicate these successes in pockets of the north American market. Architecture schools are producing students with significant knowledge in digital fabrication. However, these institutions have yet to adapt and formally collaborate with volumetric factories. As a result, they are not adequately preparing architecture students to become proficient in this new, evolving mode of design-build construction.

Notes:

1 Indiana and National low-income housing coalition data 2015-2019.

2 Source, Bank International Settlements

3 Presentation of Indiana senators Todd Young and Mike Braun. Based on data from the National Low Income Housing Coalition. NCLIHC.ORG. March 12, 2023.

4 Freddie Mac Loan Product Advisors. Data from March 2018 to February 2022.

5 Based on interviews and local neighborhood covenant and restrictions. 2024.

6 Factory_OS Press release November 2020, factoryos.com.

7 Building Trade Research Group, Building.co.UK

Bibliography:

Brannen, Paul. *Timber!: How Wood Can Help Save the World from Climate Breakdown*. Agenda Publishing, 2024. https://doi.org/10.2307/jj.15478492.

Prof. Onkar K. Chothe, Dr. Vikrant Yadav. *Optimization of Cost and Time adopting the Prefabricated Prefinished Volumetric Construction (PPVC) technique in building construction*. Neuro Quantology Volume 20 Issue 13 Page 2484-2489 doi: 10.14704/nq.2022.20.13.NQ88306. November 2022.

Li, J.; Andersen, L.V.; Hudert, M.M. The Potential Contribution of Modular Volumetric Timber Buildings to Circular Construction: A State-of-the-Art Review Based on Literature and 60 Case Studies. Sustainability 2023, 15, 16203. https://doi.org/10.3390/ su152316203

Aitchison, Mathew. Prefab Housing and the Future of Building: Product to Process. London: Lund Humphries, 2018. Print.

Levy, E et al. Advanced Envelope Research for Factory Built Housing, Phase 3--Whole-House Prototyping. Washington,

D.C: U.S. Department of Energy, Energy Efficiency & Renewable Energy, Building Technologies Office, 2014. Print.

Carr, Aute Lee. *A Practical Guide to Prefabricated Houses.* New York: Harper, 1947. Print.

Costa Duran, Sergi. *New Prefab Architecture*. Barcelona, Spain: Loft, 2008. Print.

Koones, Sheri. Prefabulous + Sustainable : Building and Customizing an Affordable, Energy-Efficient Home. New York: Abrams, 2010. Print.