COMPARATIVE STUDY OF WASTE REDUCTION PRACTICES IN MULTI-FAMILY CONSTRUCTION:

Modular Construction as a Circular Economic Solution

RESEARCH TEAM

John Killingsworth, Ph.D.
Associate Professor
Dept. Construction Management
Colorado State University
Phone: 970-491-7960
j.killingsworth@colostate.edu

Catherine Bond
Graduate Student
Dept. Construction Management
Colorado State University
Katie.Bond@colostate.edu

Jon Elliott, Ph.D.
Associate Professor
Dept. Construction Management
Colorado State University
Phone: 970-491-1845
Jon.elliott@colostate.edu

Introduction

Sustainable construction has increasingly been influencing policies, standards, and practices for how we design, create, and use the built environment. Around the world, and certainly in the United States and Canada, sustainability standards are the norm rather than the anomaly. Sustainable building metrics have been adopted by many municipalities – establishing an expectation that we are building in such a way that future generations will benefit from the same environmental conditions we enjoy today. Yet, many of the sustainable metrics employed today are fast becoming obsolete, as we have come to recognize that raising the standard is still necessary to achieve a true sustainable built environment. The dialogue on sustainability is changing from, "how do we do less harm" to "how do we do more good."

A Circular Economy (CE) in the built environment is the next step in our sustainable evolution. CE presents itself as a solution to the damaging effects of our current linear economy, one in which we extract raw materials from the earth, fabricate useful products, then when the usefulness of the product is expired we dispose of the product.

This linear process has also been described as the 'take, make, waste' approach to meeting economic demands. The linear economic approach is especially wasteful in the built environment. Construction waste alone makes up about 23% of the total landfill disposal (Bureau of Transportation Statistics, 2016) with an estimated 70% of such waste designated as recyclable. In other parts of the world, construction and demolition waste account for nearly 40% of solid waste (Wang, Kang, & Tam, 2008). According to the EPA, in 2018, 600 million tons of C&D debris were generated in the U.S. (EPA, 2024).

In a circular economy, we seek to create products that reduce the demands on the natural environment, reuse spaces, materials, and resources to prolong the useful life of buildings, and recycle rather than dispose of materials. The tenets of reduce, reuse, and recycle are an over-simplification of CE – but they are the inception of expanding fundamental principles and critically thinking about what, how and why we build. CE espouses ideas such as building with regenerative materials. And, when technical materials are used – how we ensure that those materials stay in the economic cycle indefinitely. Circular Economy stems from such ideas as Cradle-to-Cradle thinking (McDonough & Braungart, 2002), Biomimicry (Pawlyn, 2019), and Industrial Symbiosis (Lombardi & Laybourn, 2007). Circular Economy applications to the built environment are relatively new within the sustainable dialogue – but are quickly gaining traction and the Architectural, Engineering, and Construction (AEC) industry is making necessary adjustments. Within the pages of Building Revolutions: Applying the Circular Economy to the Built Environment (2016), David Cheshire asserts five fundamental principles of CE:

1.) Build in Layers
2.) Design-Out Waste
3.) Design for
4.) Design for Disassembly
5.) Material Choices

The focus of Cheshire's approach to CE is certainly materials focused – and rightfully so. Much of the opportunity for CE improvement in the built environment is in the extraction, manufacturing, distribution, and assembly of construction materials. There are, however, opportunities to apply CE principles to the entire system; thus eliminating waste in financial systems, human resources, and energy consumption – to name a few.

Figure 1: A Linear Economy Process

Modular construction is well positioned in the construction market as a circular economic solution – actively addressing each of the five principles presented by Cheshire. The Modular Building Institute (MBI) categorized modular, particularly modular volumetric, construction within Semi-Permanent, Relocatable, or Permanent Modular construction types (Dowaliby, 2023). Much of the modular volumetric construction spaces are purposefully design to be adaptable and flexible. By definition, a flexible building is one that is designed to address changing needs of the occupants – specifically interior systems. An adaptable space, by contrast, is one that is structurally designed to extend its useful life through easy expansion or contraction – 'adapting' to evolving changes of use (Addis & Schouten, 2004).

Modular construction captures this circular economic tenet from inception. The basic structural system is designed for adaptability and disassembly – thus facilitating the ability to extend useful life and value in the future. An extended useful life is significant to achieving a circular economy in the built environment. And though perfect circularity may not be attainable in our current economic demands, the effort to work towards that goal begins in designing a built environment that is capable of extending life-cycle.

Imagine numerous building material's cycles, wherein each revolution is an extension of the life of the building. With each iteration, or cycle, there is waste generated. This is particularly true in the first cycle; the construction phase, and the last cycle – the end of life.

Additional iterations of the building include remodeling, repurposing, or restoration efforts. Each of these cycles generate waste as well, but also extend the useful life of the building. Considering this significant amount of waste generated by the construction and demolition phases – a circular economy considers methods to reduce waste in each phase.

As a versatile and fundamental building material, timber contributes a significant amount of materials to the construction industry – particularly residential housing. Since the early 2000's, the U.S. consumed over 6.8 billion cubic feet of solid wood each year, and over 67% of that is for construction lumber (McKeever, 2009). Considering the volume of wood products created each year, there is a significant concern regarding the waste generated in the construction and demolition (C&D) phases. Each year, the C&D processes generate over 64 million metric tons of wood waste in the U.S. alone. Of that waste, an estimated 28 million metric tons (44%) was recovered for reuse or recycled-use (Zimmer, Weitz, Padhye, Sifleet, & Gabriele, 2018).

The concern for such significant waste produced from C&D practices is two-fold: first that bio-material contributes to the production of methane emissions – a higher contributor of trapped atmospheric heat than carbon dioxide (The Core Writing Team, IPCC, 2014), and second the rapid depletion of oxygen-producing, forested environments. Though considered a relatively rapidly renewing resource, forests are currently being cut down at a faster rate than being planted (Pearce, 2018). The concern of deforestation is that such practice depletes the very natural resources that capture carbon emissions – while also impacting the resources necessary to meet the demand of a growing population and built environment. Depletion of a significant building material translates into supply-chain problems – thus shifting economic supply and demand and potentially causing misalignment of pricing. This misalignment, however, creates an opportunity for those who can reduce waste systematically and continue to provide the built environment at a price which can be borne by society. The combination of these two environmental and economic factors causes concern for the waste practices of the construction industry.

See Figure 2 on Next Page: The Circular Economy

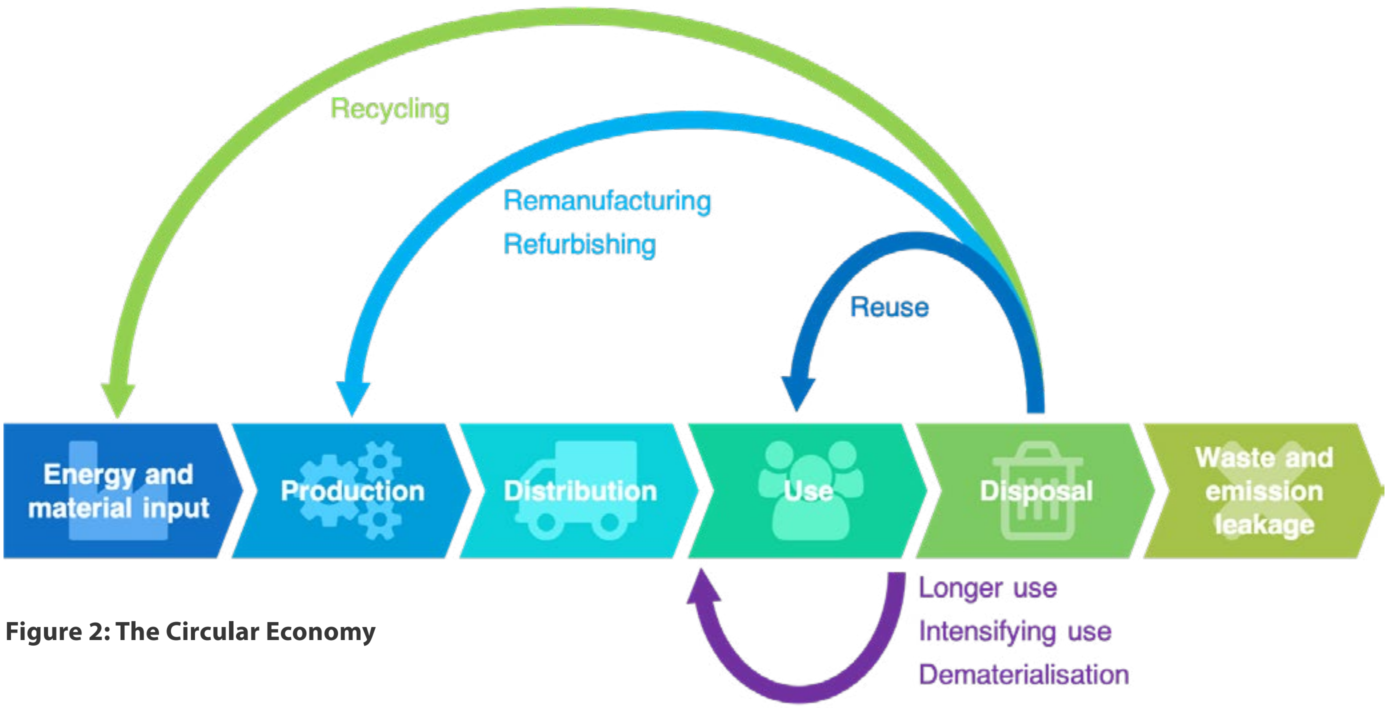

Figure 2: The Circular Economy

Research Purpose

In 2023, the Modular Building Institute (MBI) published a report entitled, "Sustainability: Making the Case for Modular Construction" (MBI, 2023). Within this report MBI called to, "dramatically change how we build in four key areas: 1. significant waste reduction, 2. lower carbon footprint/embodied carbon, 3. Relocate, renovate, repurpose, and 4. Greater energy efficiency/tighter building envelop. This call for improved performance in these four specific areas aligned with the priorities and principles of a circular economy.

In response to MBI's call to action, a research project was conducted that focused on the waste disposal, reuse, diversion and aversion practices of modular and traditional construction. A comparative case study was performed to measure the wood framing waste produced on a modular construction project versus the wood framing waste produced in a traditional, site-built construction project. With the aid of industry partners, two projects were identified that met the following criteria:

- Multi-family residential
- Wood framed, multi-story building
- Actively framing between Dec. 2022 & July, 2023
- Contractor willing to record and report wood waste
- One volumetric modular and one site-built building

In addition to these criteria, we specifically identified projects that were not to be measured or rated according to a green-building rating system, e.g. USGBC LEED, Green Globes, WELL, etc. Framing dates were established based on the need to observe site conditions during installation of modular units.

Off-Site Framed Project

The authors identified a volumetric modular project that met the aforementioned study inclusion criteria. It was noted that the modular manufacturer had implemented a practice of separating wood waste from other waste produced in the manufacturing system. Further, the wood waste generated from the plant was specifically sent to a recycling center rather than sent to the landfill, thus diverting nearly 100% of the wood cut-off waste produced at the factory.

The construction site for the modular project was in western Montana and serves as workforce housing.

It is comprised of five separate structures with a total residential floor area of 81,679 square feet. Two buildings were 3-storied, each with 12 dwelling units (36 volumetric modules). Three of the buildings were 3-storied, with 12 dormatory-style dwelling units (48 volumetric modules). The project included an additional building that was excluded from this study because the fabrication and setting of volumetric modules occurred outside of the study timeframe.

For the off-site framed project, there are no-known local ordinances requiring the sorting of construction waste. Therefore, this project's waste diversion measures were isolated to the factory framing. There were some on-site framing activities associated with the basement crawl-space. These were treated as ancillary and not considered in the waste calculations for the off-site construction process.

Figure 3: Wood Framing of Crawl Space for Off-site Project

On-Site Framed Project

Because of the wood-sorting requirement, sourcing a participant for on-site construction was more difficult. A Nevada-based contractor was initially identified, wherein the waste was being sorted by a 3rd-party contractor. The waste bins were collected, hauled to an off-site sorting facility, and the wood was separated. However, the weights were never quantified after sorting – making measurement impossible to determine. Another Denver-based company was willing to participate, but again the waste was not being sorted. A site was found in northern Colorado, where the city has an established waste diversion requirement and the general contractor provided on-site sorting bins for wood versus other waste. The roll-off bins were removed and weighed as frequently as the bin was determined to have reached capacity.

The project identified for this study was a four-storied, mixed-use, building. The primary purpose of the building is a multi-family retirement living facility. The first floors therefore serve as business, retail, and limited residential units. The first floor was cast-in-pace concrete pedestal and metal framed walls, to meet fire safety standards for retail and assembly spaces. The second floor was cast-in-place concrete with wood-framed walls. The two upper floors comprised of entirely wood-framed residential spaces and totaled 102,020 square feet of the total residential floor area was 192,201 square feet. The first floor was framed with light-gauge metal framing. Thus, a parallel comparison between the two structures could be made by isolating the measurement of wood-framing waste to the residential spaces.

Establishing Calculation Criteria

Sustainable Because framing is inclusive of walls, ceiling and floor joists, stairs and other horizontal and vertical components, a true comparison of waste must consider all three dimensions of the space. Therefore, a simple ratio of the weight of waste generated divided by the floor square footage would not provide a fair comparison, particularly when considering the density and heights of walls. Further, volumetric modular construction methodologies require a higher density of framing materials because each off-site module is entirely encased in framed walls, floor and ceiling joists. Therefore, there is typically duplicity of floors and wall systems between modules. For example, a single wall separating spaces in conventional framing would typically be comprised of a single wood-framed wall with drywall on both sides. Whereas volumetric modular construction would adjoin two wood-framed walls with drywall on interior facing sides, as well as insulation in many cases, effectively doubling the wood framing. Similarly, a module is built with ceiling joists and floor joists to maintain the stand-alone structural rigidity of each module during manufacturing and transportation. When a module is placed atop another, there is duplicity between the horizontal framing although dimensional lumber may be smaller. This translates into sound attenuation and thermal gains for modular construction, but places the modular construction at a potential disadvantage in terms of wood framing cut-off waste.

Each project was measured for wall square footage and floor square footage using the same computer-based measurement application. Having the aggregated framed square footage of horizontal and vertical square footage established a baseline for later comparison of the waste produced in each case. As previously noted, the off-site framing comprised of floor area totaling 81,670 square feet. However, the wall square footage totaled 223,008 and the ceiling & floors totaled 163,358 square feet. The on-site framed project measured 320,617 square feet of walls and 102,020 square feet of ceiling & floors. The total framed square footage for the off-site project was 386,366 and the total framed square footage for the on-site project was 422,637.

Measuring the Waste

The measurement of waste was the most significant hurdle in this study and is likely to continue to be in subsequent studies. Current economic conditions do not promote investment in sorting and recovering waste. The ease and the relatively low-cost of disposal makes it difficult to motivate contractors to capture waste as a resource rather than allocating the waste for land-fill. Jurisdictions having authority must have supply-chain systems in place in their respective communities in order to establish ordinances requiring recycling. Otherwise, significant costs pass from the contractor to the owner to the end-user without reasonable means to offset those costs. This social cost is imposed on communities as a consequence of inequities in the supply chain system (Su, 2020).

In the case of this study, we were fortunate enough to have each contractor willing to capture data according to their capabilities. However, there were limitations. In the case of the off-site framed project, dates and quantities were meticulously recorded during the timeframe of the framing activities, but weights were not provided to the manufacturer. The roll-off dumpster size was quantified and the density and condition of the wood waste was recorded. Using the approximate density and size of the dumpster, we used EPA standards to calculate the weight of the wood waste. Observations were made during the active construction of the off-site project. These observations ensured legitimacy to the waste management practices. In the manufacturing setting, we observed a systematic process for recapturing potential valuable framing cut-offs, and the waste-collection & diversion practices.

Waste Management for Off-Site Framing System

Because of the controlled environment in a factory setting, cut-off pieces of lumber and manufactured wood were captured for future use. In most cases, larger pieces are easily integrated into subsequent wall systems, often in the form of blocking or non-standard wall lengths (e.g. longer than 4' increments). The manufactured setting allows the recapture of the wood because all framing is performed in a central, accessible area. Manufactured units are moved from framing stations to subsequent stations such as electrical wiring, insulation, drywall, and so forth. This systematic process allows the building and materials to come to the framer rather than the framer moving from floor to floor and hauling potential wood framing members from place to place. Some cut-offs were repurposed as strips used to secure plastic wrap for transportation. By weight, these strips are marginally impactful and the assumption is that they are disposed of at the jobsite.

Smaller cut-off pieces (generally shorter than 12 inches) were thrown in a localized bin and then disposed of in a 30-yard dumpster. This larger dumpster was strictly enforced for wood waste only. Additional enforcement of this restriction was imposed of by a 3rd party wood recycler who inspected each load to ensure the wood was considered clean for reuse. Contaminated loads were sorted and fees assessed for the cost to dispose of 'dirty' wood. This occurred only once in the entire framing period of the off-site project. Thus, nearly all the wood waste generated during the off-site framer-manufacturer was entirely reused or recycled.

Figure 4: Reuse of Wood Framing in Factory

Figure 5 & 6: Wood Waste at Factory

Figure 7: Dedicated Wood Waste Dumpster at Factory

In many cases, two units are often manufactured as a single transportable unit. Once on site, the modules are separated were installed and necessary anchoring and utility connections made. The connecting pieces of structural lumber can and are often used by the on-site framer to finish stairs, landings, or parapets. This practice is purposeful in designing-out waste in the entire system. The manufacturer needs those structural pieces for assembly and transportation and the onsite framer needs those cut-offs for finishing site conditions. In the case of this study, we did not measure the waste of lumber generated by these on-site activities. However, the observation was that such waste was marginal in comparison – but practices of the on-site framer was similar on both sites. Thus, some allowance in the results should be considered.

During the period of framing the off-site modules for this specific project, 10 dumpsters of wood-specific waste were removed from the facility. For wood waste, high-density fill would produce approximately 4.94 tons per 30 yard dumpster. Considering the observations in the field, the

Figure 8: Adjoining Framing of Modules

Figure 9: On-Site Wood Waste Dumpster

Figure 10 & 11: On-Site Wood Waste

high-density number was used to calculate the total waste and waste per square foot of framing. Thus, at 49.4 tons of estimated wood waste divided by 386,366 square feet of framing, the estimated waste is 0.2557 pounds per square foot. Using the average tons per 30-yard dumpster of the traditional site-built project to estimate a less dense figure, we would arrive at 0.1900 pounds per square foot.

Waste Management for On-Site Framing System

For the on-site project, waste sorting and disposal was also recorded and observed. In this case, separate dumpsters on site were designated for wood waste and other waste – because of the city-enforced requirement to divert wood waste from the landfill. The general contractor was very accommodating to the research effort and provided disposal tickets for the waste throughout the framing stages of the project. Site visits were made during and after the framing stages to observe the practices.

During the framing stage of most on-site projects, little effort is made in practice to minimize the quantity of cut-off waste, and even less effort is made to make such waste available in other areas of the building. Piles of useful framing lumber litter the site. These piles are not intended in any way to make it to another area for reuse, they are intended to be disposed of.

The "Time-is-Money" mantra is predominant with a framing crew and the cost of having a laborer sort, haul, and provide access to potential cut-off waste is considered wasted time.

From the site visits made to the on-site project, observations of piles of relatively short cut-off lumber were found. These piles were not headed for reuse as blocking, but were stacked so that it would be easier to carry off to be thrown away. On-site framing simply does not benefit from the centralized framing system in a manufacturing setting. Efforts to minimize material waste at the expense of labor waste are not practiced or enforced. Despite the city's diversion policies, and the demarked dumpster categorization, and reasonable efforts by the general contractor, the subcontractor base at the on-site project simply disregarded the direction. Observations of the on-site waste sorting indicated that most of the wood waste was contaminated with other waste – not just dirty wood, but plastics, shipping waste, and other trash. Two separate site visits, captured the lack of sorting – though the latter visit was made at the end of the framing stage. At this point in the project, sorting goals (or requirements) would have been met and wood waste sorting was no longer enforced.

Figure 12: On-Site Sorting

During the framing phase, from December 7, 2022 through April 20, 2023, the reports from the waste management firm provided specific weights for each roll-off dumpster with the date of the removal. The waste management company also provided the destination of the dumpster, whether it was taken to a recycling center or landfill. Over the course of the framing phase of the on-site project, 19 dumpsters of wood waste were removed from the site. Table 1 provides the specific dates and weights in tons of each roll-off of wood waste. Dates prior to December 7th recorded dumpsters containing wood waste. However, wood-framing activities had not begun above the concrete pedestal. Upon further consideration, it was assumed that this wood waste was associated with concrete forming activities. As with the off-site framed project, and in an effort to control the comparisons – the wood waste generated prior to the framing phases were not attributed to residential wood-framing waste.

In the case of the on-site framed building, the total wood waste generated during the framing phase was 69.66 tons, based on waste hauling tickets. The average weight of each roll-off dumpster was calculated for the 19 loads, which equaled 3.666 tons per dumpster. Considering the 422,637 square feet of framing, the pounds of wood waste per square foot was calculated at 0.3296.

See Table 1 on Next Page: On-Site Disposal Data

Table 1: On-Site Disposal Data

Date	Container Size (YD)	Measured Weight (TONS)
9/21/2022	30	2.5
10/17/2022	30	1.76
10/27/2022	30	1.95
11/18/2022	30	2.97
12/7/2022	30	3.04
12/20/2022	30	4.26
12/20/2022	30	2.91
12/30/2022	30	3.5
12/30/2022	30	3.59
1/9/2023	30	3.76
1/13/2023	30	4.87
1/18/2023	30	2.23
1/19/2023	30	1
1/25/2023	30	4.71
2/10/2023	30	4.3
3/8/2023	30	4.37
3/14/2023	30	5.01
3/18/2023	30	4.47
3/28/2023	30	5.13
4/4/2023	30	4.62
4/12/2023	30	3.62
4/18/2023	30	0.61
4/20/2023	30	3.66
4/29/2023	30	2.77
5/15/2023	30	2.65
5/20/2023	30	2.05
5/22/2023	30	3.57
5/24/2023	30	2.81
5/26/2023	30	3.37
	TOTAL:	96.06
	MEAN (Framing):	3.67
	Std. Dev. (Framing):	1.27
	MEAN (Framing w/o Outliers*):	4.00

**Outliers defined as 2 standard deviations from the mean.*

Comparison of Off-Site to Site-Built Framing Waste

In every comparison made, off-site framing produced less waste. Applying the highest density factors of wood-filled dumpsters from the EPA (4.94 tons per 30 yard dumpster), the offsite framed multi-family residence produced less waste than site-built (22.4% less waste). Table 2 provides a side-by-side comparison of the framing waste results. Taking into account that all dumpsters may not be 'densely packed', the average density of the modular roll-off waste was also calculated based on the site-built project's average of 3.67 tons per 30 yard dumpster. At 3.67 tons per 30 yard dumpster, the results demonstrate significantly lower amounts of waste for the volumetric modular project, only 57.6% of the wood waste generated, or 42.4% less waste than the site-built project.

Often, construction waste studies calculate waste in pounds per gross floor area (GFA) ((Poon, Yu, Wong, & Cheung, 2004; Jaillon, Poon, & Chiang, 2009; Hao, Chen, Zhang, & Loehlein, 2021). Using only GFA of the wood framed levels, the results no longer favor off-site construction. Table 3 provides that comparison.

Table 2: Comparison Table of Results

	Modular	*Site Built*
Framing Dates	2/10/2023 – 6/8/2023	12/5/2022 – 4/20/2023
Framing Days	118	136
Walls (SF)	223,008	320,617
Floors (SF)	163,358 *Floor & ceiling*	102,020 *Level 2: Slab (not Included) Level 3 & 4: Wood*
Total SF of Framing	**386,366**	**422,637**
Wood Waste Removal (30 yards, each)	10	19
Wood Waste Removal (30 yards, tons)	36.7 – 49.4 (estimate)	69.66 (measured)
LBS/SF (measured)	n/a	0.3296
LBS/SF (estimate) (3.67 tons/30 yards)	0.1900	0.3300
LBS/SF (estimate) (4.94 tons/30 yards)	0.2557	0.4442

Table 3: Comparison Table of Per-Square Foot Results

	Modular	*Site Built*
Wood-Framed Gross Floor Area (GFA)	81,679	156,697
Wood Waste Removal (30 yards, tons)	36.7 – 49.4 (estimate)	69.66 (measured)
LBS/SF (measured)	n/a	0.8891
LBS/SF (estimate) (3.67 tons/30 yards)	0.8986	
LBS/SF (estimate) (4.94 tons/30 yards)	1.210	

Interpreting the Results

When interpreting these results, a few notes of caution should be considered. This comparison does not directly account for wall density in the framed space. However, it does demonstrate that off-site waste management still performs very well compared to site-built practices. Caution should be taken using these figures as it introduces a number of variables which would be considered confounders to the true results.

For example, observations on site were difficult to verify when wood waste was mixed with non-wood waste for the site-built project. Mixed-waste observations were made immediately after the documented framing phase. The concern exists that some waste that was not attributed specifically to residential framing may not have been included in the total weights. The research team did not observe every dumpster at every disposal date. For the onsite project, seven of the 19 loads were taken to a wood recycling center, while the remaining 16 were taken to a landfill. The county facility did not allow for wood-specific disposal, so these 16 loads were not diverted. Only seven loads specifically taken to the recycling center were diverted from the landfill.

This activity introduces two conditions to consider. First, that there was likely non-wood waste in the other 16 dumpsters such that disposal at the recycling center was not allowed. If that is the case, then an estimated factor must be introduced to consider how much of the site-built waste was contaminated, non-wood. By weight, the non-wood waste would have to account for 25% to 43% for site-built conditions to out-perform off-site conditions. Observations made by the research team do not support those conclusions, but it does raise an ongoing concern for future studies. Even in locations where wood waste sorting and diversion is required, there is a need to monitor human behavior to gain a complete picture of wood waste disposal.

The second condition raised by this activity is a more favorable result for this study. In the case of this particular volumetric modular manufacturer, all wood waste was recycled during the factory construction phase. In contrast, we only know of seven of 19 dumpsters for the traditional site built project that were specifically sent to recycling. When examining these results under the Circular Economy lens, off-site modular framing practices clearly outperform site-built practices. In this case 100% of the estimated 49.4 tons of waste generated during framing was sent to a recycling center. Wood recycling centers either make use of wood stock in its current condition, or down-cycle the material as wood pellets, mulch, or livestock bedding. Either solution keeps the product in the economic cycle or introduces it safely back into the biosphere. On the other hand, wood waste sent to the landfill is economically costly and also contributes to producing methane gas, a significant contributor to environmental pollution and heat trapping.

Conclusion

This study compared two multi-family housing projects, both wood-framed and both located in the mountain-west states of the U.S. As noted, project characteristics and data collection challenges introduced limitations to the study. Therefore, the results of this case study should be generalized with caution and further research among a larger sample of projects would contribute to validation of the study findings at large. Observations were limited to those made by the researchers, while some results required trust in the information provided by the manufacturer and general contractor of the off-site project and site-built project, respectively. It should be noted that both the manufacturer and the general contractor are leaders in the industry and community, and both are actively engaged in moving toward a more sustainable built environment. Without their trustworthy engagement, the data and subsequent results of the study would have proven even more difficult to obtain.

There are more areas of waste reduction to be studied, specifically other materials such as concrete, masonry, drywall, and shipping/handling materials. These four categories of materials are observed to produce high levels of waste without consideration for reuse, recycling, or downcycling. Yet current practices may provide circular economic options to reduce such waste. Further studies must seek to empirically measure more categories of waste. And, additional studies should be performed on wood and metal framed waste. More case studies will ultimately lead to methods to reach generalized, statistically strong evidence – which in turn informs policy makers and necessary change to our methods.

The fundamental conclusion of this study is that off-site framing practices achieve the following, notable results:

1.) Reduction of at least 23% of wood waste, (compared by framed square footage)
2.) Nearly eliminates ALL methane producing landfill waste by practice
3.) More effectively reuses wood cut-off waste by practice, and
4.) Achieves higher 'circularity' for wood cut-off waste.

References

Addis, W., & Schouten, J. (2004). *Principles of design for deconstruction to facilitate reuse and recycling.* Ciria.

Bureau of Transportation Statistics. (2016). *Municipal Solid Waste and Construction & Demolition Debris.* Washington D.C.: United States Department of Transportation.

Cheshire, D. (2016). *Building Revolutions: Applying the Circular Economy to the Built Environment.* Newcastle upon Tyne, UK: RIBA Publishing.

Dowaliby, M. (2023, March 1). *Modular vs. Stick Built and A Case for the Future of Construction.* Retrieved from Modular.org: https://www.modular.org/2023/01/12/modular-vs-stick-built-and-a-case-for-the-future-of-construction/

EPA. (2024). *Sustainable Management of Construction and Demolition Materials. United States Environmental Protection Agency.* Retrieved March 13, 2024, from https://www.epa.gov/smm/sustainable-management-construction-and-demolition-materials

Hao, J., Chen, Z., Zhang, Z., & Loehlein, G. (2021). Quantifying construction waste reduction through the application of prefabrication: a case study in Anhui, China. *Environmental Science and Pollution Research,* 28. https://doi.org/10.1007/s11356-020-09026-2/Published.

Jaillon, L., Poon, C., & Chiang, Y. H. (2009). Quantifying the waste reduction potential of using prefabrication in building construction in Hong Kong. *Waste Management,* 29(1), 309–320. https://doi.org/10.1016/j.wasman.2008.02.015.

Lombardi, D. R., & Laybourn, P. (2007). Industrial Symbiosis in Action. *Forestry & Environmental Studies Publications,* Series 32. https://elischolar.library.yale.edu/fes-pubs/32.

MBI. (2023). *Sustainability: Making the Case for Modular Construction.* Washington D.C.: Modular Building Institute.

McDonough, W., & Braungart, M. (2002). *Cradle to Cradle: Remaking the Way We Make Things.* New York, NY: North Point Press.

McKeever, D. B. (2009). *Estimated Annual Timber Products Consumption in Major End Uses in the United States,* 1950-2006. Madison, WI: United States Department of Agriculture.

Pawlyn, M. (2019). *Biomimicry in Architecture, 2nd Edition.* Routledge.

Pearce, F. (2018, October 9). *Conflicting Data: How Fast is the World Losing its Forests?* Retrieved from Yale School of the Environment: https://e360.yale.edu/features/conflicting-data-how-fast-is-the-worlds-losing-its-forests

Poon, C. S., Yu, A., Wong, S. W., & Cheung, E. (2004). Management of construction waste in public housing projects in Hong Kong. *Construction Management and Economics,* 22(7), 675–689. https://doi.org/10.1080/0144619042000213292.

Su, Y. (2020). Multi-agent evolutionary game in the recycling utilization of construction waste. *Science of the Total Environment.* https://doi.org/10.1016/j.scitotenv.2020.139826.

The Core Writing Team, IPCC. (2014). *Climate Change 2014 Synthesis Report.* Geneva, Switzerland: Intergovernmental Panel on Climate Change.

Wang, J. Y., Kang, X. P., & Tam, V. (2008). An investigation of construction wastes; an empirical study in Shenzhen. *Journal of Engineering, Design and Technology,* 6(3), 227-236.

Zimmer, A. T., Weitz, K., Padhye, A., Sifleet, S., & Gabriele, H.-S. (2018). *Wood Waste Inventory: Final Report.* Cincinnati, Ohio: United States Environmental Protection Agency (www.epa.gov/research).