THESIS

WASTE REDUCTION IN MULTI-FAMILY CONSTRUCTION: A COMPARATIVE STUDY

Submitted by

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Department of Construction Management

In partial fulfillment of the requirements

For the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Spring 2024

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ABSTRACT

WASTE REDUCTION IN MULTI-FAMILY CONSTRUCTION: A COMPARATIVE STUDY

In a linear economy, construction and demolition (C&D) waste is considered to have zero value and, thus, most C&D waste ends up in landfills. However, key stakeholders have begun to improve waste management practices, focusing on waste reduction, material reuse and recycling in an effort to meet Circular Economic and Zero Waste targets. Modular construction presents itself as a sustainable alternative to traditional, site-built construction, and an important component of the emergent circular economy in the built environment. The advertised advantages to modular are reduced construction time, reduced energy consumption, reduced onsite pollution, and reusability of modular units. This study compared wood framing waste during the construction of two multi-family projects – one volumetric modular and one traditional site-built. I found evidence to suggest that the volumetric modular manufacturing process allows for greater waste aversion and diversion than the site-built environment. Overall, the modular project produced 20-33 fewer tons of wood than the traditional site-built project, which, according to the methods from Toochi (2018) is approximately 10 -16.5 tons of sequestered CO_2 per year. This was quantified through waste records, project plans, and site observation. This study is an important step in the growing body of work in circular economics in the built environment and the sustainability of modular construction.

ACKNOWLEDGEMENTS

This journey started in earnest during an independent study in Circular Economics with my advisor, Dr. Killingsworth, and Drs. Mehany and Burgoon in Spring 2021. Thanks to their encouragement, I applied for the MS program in Construction Management and was accepted in Spring 2022. It hasn’t always been easy, and it would not have been possible without the hours of conversation, expertise, encouragement and support of my advisor and my committee, Drs. Elliott, Conrad, and Schaller.

Thanks to Paul, Danny, Rick, and CJ for sharing their time and modular expertise. I gained a wealth of insights during my onsite visits and through follow-up emails and phone calls. Thanks also to Matthew for sharing his time and expertise for the site-built project. I’m also grateful to the many MSW professionals who took the time to discuss their operations with me. In particular, Duane and Alex who share a passion for achieving circular economic solutions.

It truly takes a village to be a parent-student. This would not have been possible without the support of my husband, Frank, and our childcare professionals: Mandi, Melody, and Miss B. Also, thank you to my kids and my parents, who have been incredibly patient and supportive while I pursue this degree.

RESEARCHER BIO

Catherine E Bond (she/her), LEED Green Associate, is a graduate student in Construction Management at Colorado State University. Her research focuses on Circular Economics, Deconstruction, C&D Waste Aversion and Diversion, and Sustainability in Construction. She works as a Sustainability Associate for Institute for the Built Environment and a Graduate Teaching Assistant in the Construction Management department. She has held Research Assistant positions in Circular Economics in the Built Environment (SoGES grant), Deconstruction (FRWD grant), and Sustainable Research Network development (NSF planning grant). This work is partially funded by a grant from the Modular Building Institute (MBI).

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

According to the EPA, in 2018, 41 million tons of construction and demolition (C&D) wood waste were generated and over 73% of that waste went into the landfill. The remaining 27% went to compost and mulch, manufactured products, and fuel (US Environmental Protection Agency, 2020). Locally, according to a 2016 report from Larimer County, Colorado, 19% of the C&D waste in Larimer County Landfill waste by weight was wood, with another 7% as treated and painted wood (Sloan-Vasquez-McAfee Municipal Solid Waste Advisors, 2016).

According to the EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021* (2023), Municipal Solid Waste (MSW) landfills accounted for nearly 14.3 percent of human-related methane emissions in 2021. Globally, the waste sector accounts for roughly 20 percent of human-related methane emissions (GMP, 2023). Methane is more than 28 times as potent as carbon dioxide at trapping heat in the atmosphere (IPCC, 2014). The Global Methane Pledge (GMP) was developed at COP26 with the goal of reducing methane emissions by at least 30% from 2020 levels by the year 2030. At COP28, a new initiative to dramatically reduce methane emissions in the waste sector was launched: Lowering Organic Waste Methane (LOW-Methane). Organic waste includes any biodegradable material from a plant or animal, including wood from construction. Reducing human-related methane emissions "is the single fastest way to keep the 1.5°C temperature limit within reach" and improves public health and agricultural productivity (GMP, 2024).

Concepts from circular economics in the built environment (CEBE) could be used to avert or divert C&D wood waste from landfills and reduce methane emissions. Waste aversion refers to materials that do not enter the waste stream – in this case, wood waste that does not enter the waste stream during construction. In the design phase, wood waste can be averted by designing out waste or, put another way, designing for efficient use of resources. As an example, for wood framing, this usually means choosing standard wall heights to limit cutting during construction. During the construction phase, wood waste can be averted when cut wood is used in other parts of the project. For unavoidable wood waste, another CEBE concept is to think about waste as a resource. For construction, this means diverting wood waste from the landfill to be repurposed as mulch or fuel.

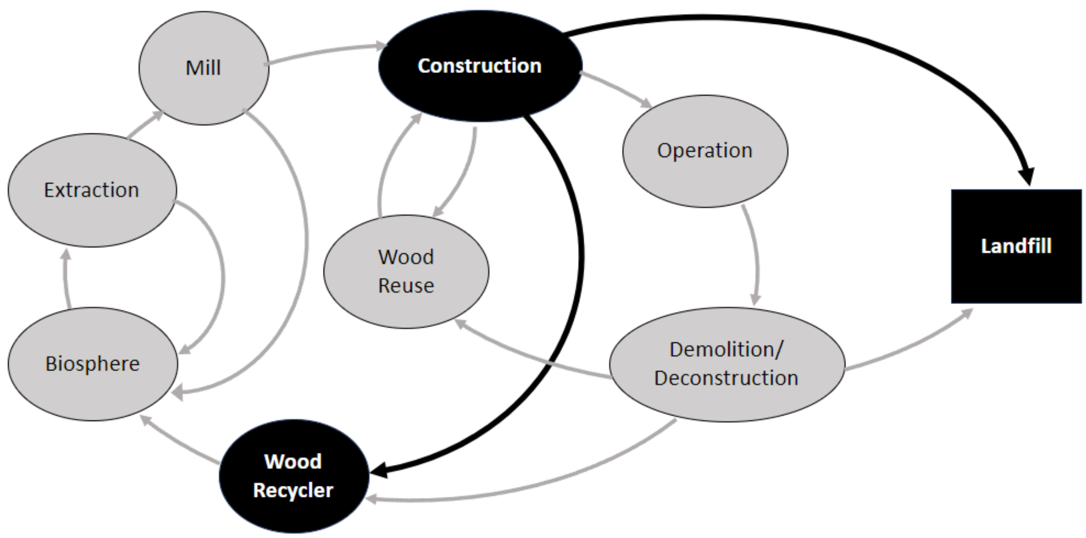

Figure 1 Construction wood lifecycle.

This study investigated the overarching research question: does volumetric modular construction produce less wood framing waste than traditional site-build construction? Figure 1 shows the focus of this study in the context of the construction wood lifecycle in a circular economy. Processes and arrows in black (Construction, Landfill, Wood Recycler) represent the focus of this study. Processes and arrows in gray demonstrate the full lifecycle of construction wood in a circular economy.

For this study, a literature review was conducted to determine existing wood waste measurement in construction. Figure 2 shows the research schedule for this study. In early 2023, two wood-framed, multi-family projects were identified that were source-separating wood waste but not seeking a "green" certification (LEED, Green Globes, e.g.). In summer 2023, I measured the square footage of wood framed walls, floors, and ceilings (modular only) using OST. Framing dates and waste tickets were provided by the contractors for both projects. The modular project provided pick-up dates for the 30 yard dumpsters but was not weighed. The site-built project provided pick-up dates and weight of each load. I used this information to determine an estimated wood waste rate for the modular project. The wood waste produced on the modular project was between 0.1900 lb/SF and 0.2557 lb/SF. The wood waste produced on the site-built project was 0.3296 lb/SF.

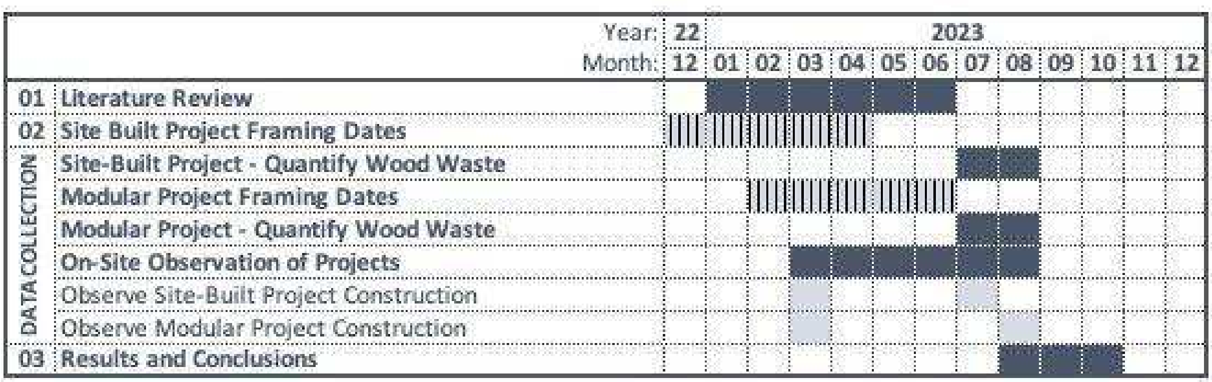

Figure 2 Research schedule.

This study provides evidence that modular construction practices may result in less wood framing waste than traditional site-built construction. This study represents an important step in the growing body of work in circular economics in the built environment and the sustainability of modular construction. The insights gleaned could be used by contractors to strengthen waste management practices and could be used to develop future studies related to waste diversion in modular, off-site construction and traditional, site-built construction.

CHAPTER 2: LITERATURE REVIEW

2.1 Circular Economics in the Built Environment

The Ellen MacArthur Foundation defines a circular economy as "an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through superior design of materials, products, systems, and within this, business models" (MacArthur, 2013, p. 7).

Circular Economics (CE) breaks the Take – Make – Waste linear economic cycle and instead treats waste as a resource. Ideally, materials can be retained at their highest value and remain in the economic cycle. There are several ways to accomplish this, depending on the material or building component. If a material can no longer remain in the economic cycle in its highest form (either by retaining or reusing), it can be recycled or composted if it can be split into biological or technical components. Table 1 shows options for managing waste as a resource. Retrofit, Refurbish, and Remanufacture are not options for wood waste management. During construction, wood waste can be averted if it can be retained and used elsewhere within the project. Smaller wood scraps can be "composted" – sent to a wood recycler where it is turned into animal bedding or mulch. At the end of life for the building, it can be deconstructed, and wood can be reclaimed for use on new construction projects.

Table 1 Waste as a Resource (Cheshire, 2019, pp. 9–11)

Retain	The primary goal of CE is to retain materials and building components at their highest value.
Retrofit	Adapt and update buildings and their components.
Refurbish	Expensive components can be refurbished and reused.
Reclaim/Reuse	Reusing materials has a lower environmental impact than refurbishing and remanufacturing.
Remanufacture	Reassemble to meet or exceed OEM standards.
Recycle/Compost	Avoid contaminating materials so they can be split into biological and technical components at the end of life and then be returned to the industrial cycle through recycling or the biosphere through composting.

Circular Economics in the Built Environment (CEBE) has several principles that can promote sustainable, regenerative buildings. Table 2 defines these principles. Deconstruction and waste reduction can be impacted through all of these principles. Building in layers will extend the life of a building and its expensive components. Building in layers also aids in deconstruction at the end of life of the building. Designing out waste involves lean design and construction principles. This contributes to the overall goal of waste reduction and reduced use of raw materials in construction. Offsite volumetric modular construction uses standardization as a way to design out waste. Design for adaptability extends the life of the building, limits C&D waste in landfills, and can support deconstruction if designed with disassembly in mind.

Table 2 Principles for Circular Economics in the Built Environment (Cheshire, 2019, pp. 32–33)

Building in layers	Various elements have different lifespans. Allows for easier maintenance, adapting to new uses, and components are easier to reclaim at end of life.
Designing out waste	Reduces the demand for raw materials by using reclaimed materials and remanufactured products. Lean design and construction also contribute to reduced waste during the construction phase.
Design for adaptability	Buildings that can adapt to different uses can be preserved for longer.
Design for disassembly	Allows building components and whole buildings to be reused. Building components are considered assets that are independent of the site and retain value for longer. When materials can be extracted, they are more valuable and, with the use of BIM or other inventory software, buildings can become "materials banks".
Selecting materials	Materials can be split into biological and technical components so they can either be composted and returned to the biosphere or remain in the industrial loop through reuse or recycling.

2.2 Zero Waste Concept & Waste as a Resource

In circular economics, the idea of waste is eliminated and, instead waste from one process becomes a resource in another process. Waste can either be reduced through aversion or diversion. In aversion, wood remains in use at its highest value – depending on their size, scraps can be retained and used within the project (blocking, e.g.). Only the smallest pieces are then placed in a bin for removal. Ideally, if they are not needed within the current project, larger wood pieces and excess wood can be retained at its highest value and used in other construction projects. This method is labor-intensive and not currently utilized proactively. Construction firms will sometimes donate unused wood to schools and other projects when asked but don't generally reach out to these groups when they have excess materials, e.g.

Waste that cannot be used within the project or on another project can then be diverted from the landfill through recycling or composting. Wood waste can be sorted into three categories for disposal: green, clean, and treated. Green wood is trees and shrubs and can be composted or ground into mulch. In C&D, green wood waste is typically generated during the site clearing phase. Clean wood is untreated, unpainted dimensional lumber. It can often be accepted at the same facilities that accept green wood. At compost and landscape facilities, clean wood is made into mulch or livestock bedding. Treated wood is chemically treated to prolong its life. Painted wood is in the same category. In the subject locations for this study, there were no available options for recycling treated or painted wood – it all goes to the landfill.

In addition to the above uses, there are several options for down-cycling clean wood waste from construction. According to the National Waste Association (Esposito, 2021), clean wood waste can be used to create the following:

- Manufacture of chipboard and fiberboard
- Manufacture of presswood pallets
- Production of pathways and children's play surfaces
- Bedding materials for animals
- Production of remanufactured products, including fiber composites
- Landscaping mulch and architectural components
- Fuel sources for commercial markets, including logs and fuel chips
- Biofuel for WtE (Waste to Energy) plants, specifically incineration plants
- Liquid fuels e.g., ethanol and methanol

End-use markets are location-dependent, however, both projects had similar options available for wood waste diversion. The wood waste that was diverted from the site-built project was sent to a company that turns clean wood into mulch for residential and commercial use. Smaller wood pieces in that facility are ground into bedding for livestock. The modular project sent its clean wood to a company that grinds it up for livestock bedding only. From a CE perspective, this is returning biological materials into the biosphere – the wood chips will continue to biodegrade into the soil.

Larimer County and the state of Colorado, where the site-built project is located, are working on a plan to divert organic materials from the landfills. Studies are underway to find solutions to clean and treated wood. For clean wood, in addition to compost, Larimer County is considering biochar and gasification. "Biochar is a highly absorbent, specially produced charcoal with unique properties originally used as a soil amendment" (Biochar Now, n.d.). Biochar is produced using slow pyrolysis: heating wood or other plant material with little or no oxygen. Biochar improves soil fertility.

Wood gasification is where wood is burned at a very high heat, with little to no oxygen. A synthetic gas (syngas) is released. Syngas is considered a clean, renewable energy source (Alternate Heating, 2022).

2.3 Overview of Construction Wood Waste Measurement

Quantifying construction wood waste is an important step toward minimizing wood waste. Wu et al. (2014) conducted an analytical review of construction and demolition waste measurement in the literature. Their study organized the literature by measurement at the project level or regional level. Within the project level, the most common method of measurement was "site visit." They classified site visit measurement as either direct or indirect. For papers that used direct measurement, the researchers typically created a pyramid of material, weighed a few samples, and used that measurement as the basis for determining the weight of the waste generated. In indirect measurement, the researchers used weight information from the haulers to determine the waste generated on a project. Table 3 is a review of project level waste measurement in the literature.

Table 3 Review of Project Level Waste Measurement

Reviewed Paper	***Direct/ Indirect***	***Summary of Findings***
Gavilan & Bernold (1994)	Direct: Volume of materials (m^3)	Residential construction. Observed that framers generally grab a new piece to cut to size, rather than use scraps.

Reviewed Paper	*Direct/ Indirect*	*Summary of Findings*
Bossink & Brouwers (1996)	Direct: Weight (%)	Residential construction. Did not quantify wood waste.
McDonald & Smithers (1998)	Indirect: Volume of materials (m^3) based on bin size	Commercial construction. Wood was mostly formwork. 17.4% recycled. Limited options for wood recycling. Recycled wood turned into mulch.
Formoso et al. (2002)	Indirect: Weight (%)	Primarily residential. Did not include wood waste. Quantified direct (total loss, e.g.) and indirect waste (human error, e.g.).
Poon et al. (2004)	Indirect: Total waste (W) calculated by multiplying truck volume (m^3) by number of trips. Waste index = W/GFA (m^2 gross floor area)	Public housing. Timber waste from formwork required disposal.
Begum et al. (2006)	Indirect: Weight (tons and %)	Net benefit of onsite reuse and recycling is estimated to be 2.5% of the total project budget.
Kelly & Hanahoe (2008)	Indirect: Visual assessment of mixed waste container. Converted volume to tons.	Generated a waste rate in kg per m^2. Residential = 70.27 kg/m^2 (14.39 lb/ft^2).
Lau et al. (2008)	Direct: Weighed waste onsite.	Generated a waste rate in tons per hectare for residential construction in Malaysia. Wood waste was 35% to 69.5% of total waste composition.
Jaillon et al. (2009)	Indirect: Calculated waste per construction floor area by multiplying number of truck loads by a waste factor.	Average waste reduction was about 52% when adopting prefabrication.
Nagapan et al. (2013)	Direct: Volume of materials (m^3)	Residential construction. Timber was the most waste by volume. Waste management plans (WMP) not followed.
Li et al. (2014)	Indirect: Simulation model testing adoption of prefabrication through different public policies.	Model shows cost and waste savings with prefabrication compared to site-built construction.
Hao et al. (2021)	Indirect: Simulation; Volume & Weight; Multiplied waste rate by gross floor area (kg per m^2)	Overall waste reduction when using prefabricated units was 36% by volume and 26% by weight.

The case studies found that waste management plans were not followed (Nagapan et al., 2013) and observed that framers would cut a fresh piece of wood, rather than find an appropriate scrap (Gavilan & Bernold, 1994). Other studies demonstrated that wood waste from concrete formwork was a large contributor to the landfill (McDonald & Smithers, 1998; Poon et al., 2004).

2.4 Volumetric Modular Construction

Volumetric modular construction allows for 70% to 95% of a building to be constructed offsite in factory conditions and transported for onsite assembly (Thai et al., 2020). Modular manufacturers tout the environmental benefits of offsite modular construction, but the research is less clear (Karthik et al., 2020; Quale et al., 2012). Advertised benefits include a reduction in material waste during construction, reduced transportation emissions for workers, and improved indoor air quality for workers and building inhabitants (Guerdon, 2020). Volumetric modular construction is well-suited for several commercial construction applications: hospitality, healthcare, education, and multi-family construction, including affordable housing, student housing, and senior housing. Figure 3 shows the market share of each commercial sector in 2022 (Modular Building Institute, 2023).

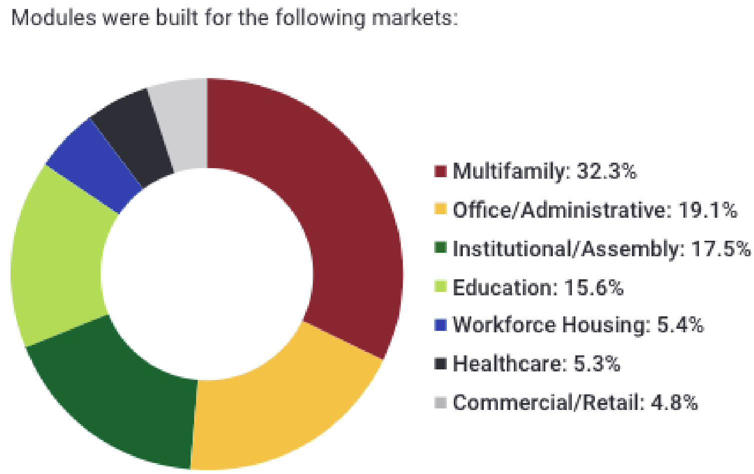

Figure 3 Modular construction sectors in 2022. Image credit: MBI.

In North America, the permanent modular construction industry accounted for 6% of all new construction starts and exceeded $12 billion in 2022. The market share has nearly tripled since 2015, when it was 2.14% (Modular Building Institute, 2023). MBI estimates that there are 255 modular manufacturing companies in North America generating revenue in the commercial modular industry. Multi-family construction represents about one-third of the factory output and is the largest market for the modular industry.

2.5 Problem Statement

Current design and construction practices follow a linear model where waste is considered to have zero value and typically ends up in the landfill. As key stakeholders (government leaders, developers, manufacturers, contractors) begin to work toward Zero Waste goals, C&D waste, representing nearly 30% of landfill waste, is an important leverage point in waste diversion practices (*Sustainable Management of Construction and Demolition Materials | US EPA*, n.d.). In 2018, 73% of nearly 41 million tons of C&D wood waste went to landfills in the United States. The remaining 27% went to compost and mulch, manufactured products, and fuel (US Environmental Protection Agency, 2020).

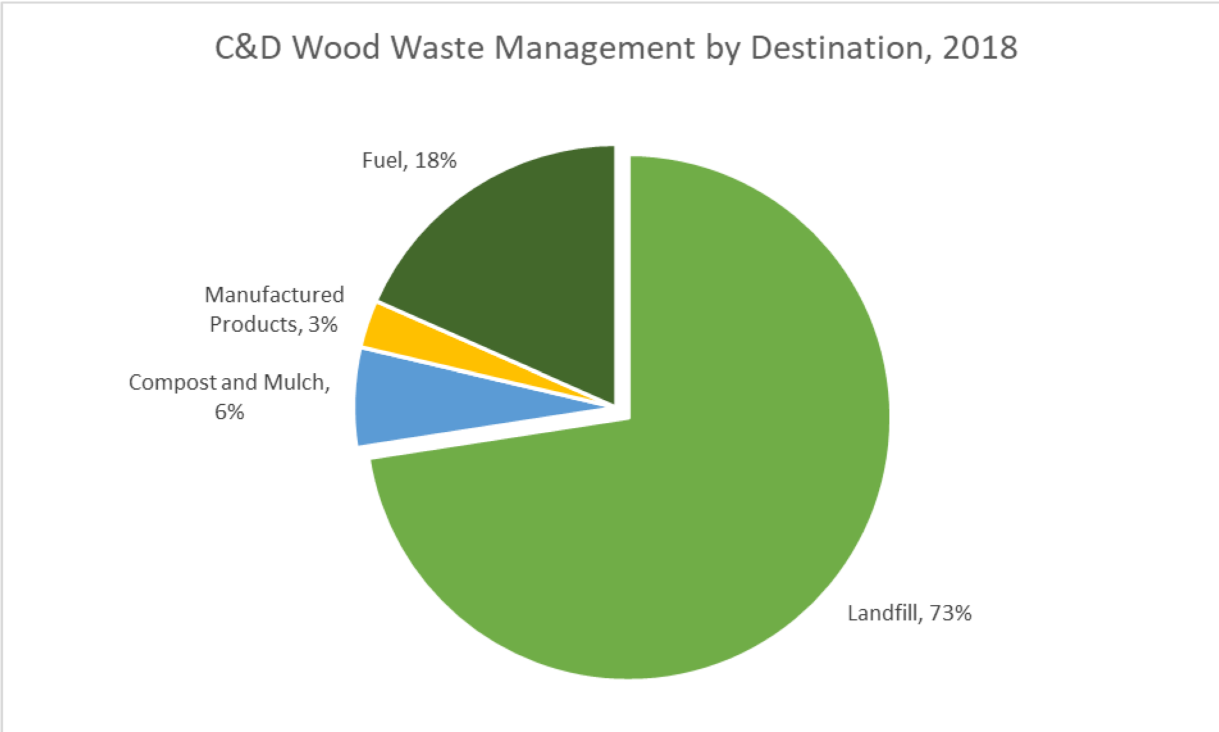

Figure 4 C&D Wood Waste Management, 2018; Source: EPA: Advancing Sustainable Materials Management: 2018 Fact Sheet

In 2016, 17% of the Larimer County Landfill waste by weight was wood. This is the aggregate of municipal solid waste (MSW), Self-Haul, Commercial, and C&D waste. For C&D alone, 19% was wood waste, with another 7% as treated and painted wood. According to the report, "[wood waste] can be readily separated by generators, or by hand at a landfill or transfer station" (Sloan-Vasquez-McAfee Municipal Solid Waste Advisors, 2016). This, along with the work that is already happening at the state and local levels, represents a great opportunity for additional circular economics in the built environment research.

Additionally, GHG emission reduction goals are being set at the international, national, state, and local levels (Boulder County, 2023; GMP, 2024; State of Colorado, 2021). According to the EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021* (2023), Municipal Solid Waste (MSW) landfills accounted for nearly 14.3 percent of human-related methane emissions in 2021. Globally, the waste sector accounts for roughly 20 percent of human-related methane emissions (GMP, 2023). Methane is more than 28 times as potent as carbon dioxide at trapping heat in the atmosphere (IPCC, 2014). The two common solutions to reduce organic waste in landfills is diversion and to generate biogas (State of Colorado, 2021). Both solutions support a circular economy.

Modular construction advertises itself as a sustainable alternative to traditional site-built construction (Modular Building Institute, 2023), but additional research is needed to compare and quantify the different construction methods.

2.6 Research Question

The purpose of this study was to compare the framing wood waste produced in two multifamily projects through the application of case study methodology. Thus, the study investigates the overarching research question: does volumetric modular construction produce less wood framing waste than traditional site-built construction?

In an attempt to answer the overarching question, I developed a comparative case study comparing wood framing waste from site-built construction to wood framing waste from modular construction. Using waste tickets provided by the contractors, I compared the wood waste that was separated onsite for each project. I also visited each project during the framing period and visited the modular project during the modular “set” phase in order to gain a better understanding of onsite waste management practices. I used this information to answer the research question: Is less wood-framing waste produced on the volumetric modular multi-family case project (Modular1) than on the traditional, site-built multi-family case project (Site-Built1)?

$$H_0\text{: Wood Waste}_{Modular1} \geq \text{Wood Waste}_{Site\text{-}Built1}$$

$$H_1\text{: Wood Waste}_{Modular1} < \text{Wood Waste}_{Site\text{-}Built1}$$

The null hypothesis states that the wood waste produced by the modular case project is greater than or equal to the wood waste produced by the traditional, site-built case project. The alternative hypothesis states that the wood waste produced by the modular case project is less than the wood waste produced by the traditional, site-built case project.

CHAPTER 3: METHODOLOGY

For this study, I started with a literature review (Chapter 2) where I examined the existing literature related to CEBE, with a focus on waste as a resource, designing out waste, and wood waste research specific to construction. From this literature review, I identified a gap in the literature comparing construction waste between traditional site-built construction and volumetric modular construction.

The research methodology for this study, discussed in Chapter 3, was a convenience sample for a comparative case study of two construction projects. Though convenience sampling is limited in that it is not representative of a population, it is useful when researchers have limited time, budget and workforce (Etikan, 2016). Case studies are one of the most commonly used research strategies in social research (Priya, 2021). Convenience sampling was chosen for a few reasons. First, while wood-framed multi-family construction is common, source separating waste materials is not. Convenience sampling allowed me to identify a traditional site-built project in a location where waste sorting is required by municipal code. Second, I needed to confirm that waste is, indeed, being separated during construction. Even when required by policy or municipal code, waste sorting can be inconsistent. Hence, necessitating job site visits to observe the practices, procedures, and compliance with the waste-sorting standards. Third, sharing sensitive data and allowing observations of practices requires trust and relationships, which is more easily achieved with convenience sampling. The selected projects were wood-framed, multi-family construction that had existing waste sorting practices in place.

For data collection, I quantified the wood framed wall and floor square footage of each project using On-Screen Takeoff (OST) and used source-separated waste documentation from the contractors to compare the waste generated using pounds per wood square footage as the metric.

In Chapter 4, I calculated the wall square footage in addition to the floor square footage because there are variations in wall density, room size, and shape within multi-family design, which would impact the wood waste measurement. In addition, the research included site observations from both projects. Site visits were performed at strategic times during fabrication, install, and site-built framing phases.

In Chapter 5, I compared the quantity of waste generated (lbs/SF) using the wood-framed wall area and floor area combined. I discuss my conclusions, limitations of the study, and paths for future research (Figure 5). I found evidence to suggest that modular construction the volumetric modular manufacturing process allows for greater waste aversion and diversion than the site-built environment.

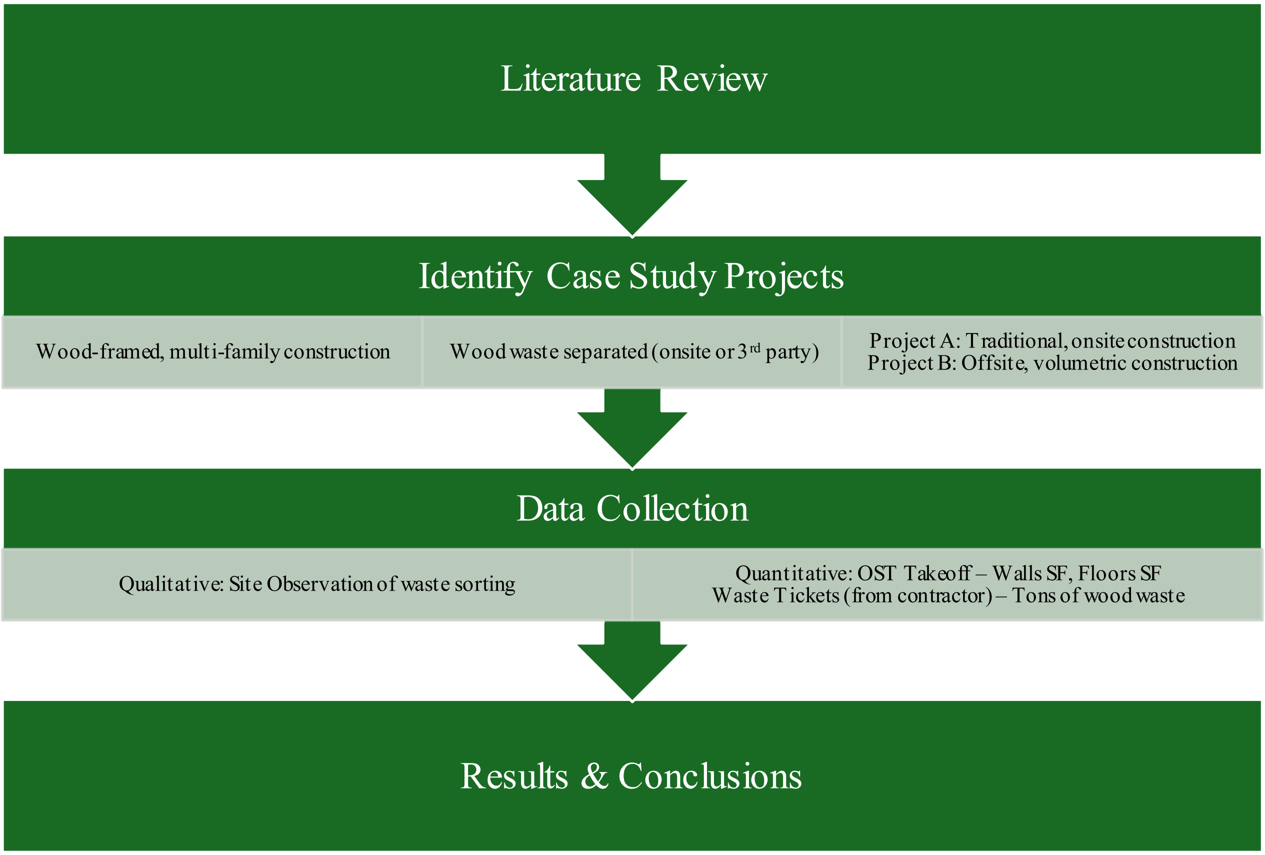

Figure 5 Research Methodology

3.1 Project Characteristics

The two projects were selected based on the following criteria:

1. Construction type must be wood-framed, multi-family
2. Construction project must separate waste (either source separated or 3rd party)
3. Project A must utilize traditional, onsite construction methodology.
4. Project B must utilize offsite, volumetric construction methodology.

3.1.1 Volumetric Modular Project Characteristics

The volumetric modular project consisted of five wood-framed, multifamily structures. The total residential floor area for the five buildings was 81,679 SF. Two of the buildings were 3 stories, with 12 dwelling units each, comprised of 36 modules (Figure 6). Three of the buildings were 3 stories with 12 dwelling units each, comprised of 48 modules (Figure 7). The original design included four identical buildings, however, building 900 was excluded from the study because it was disrupted during the factory construction period and the site construction of the fourth building has been delayed until Spring 2024. There are no known local ordinances that require wood waste sorting during the construction period – both in the factory location and the onsite location. Wood waste was voluntarily sorted during factory construction. Wood waste was not sorted during the onsite construction period. This project did not pursue green building certification such as LEED or Green Globes.

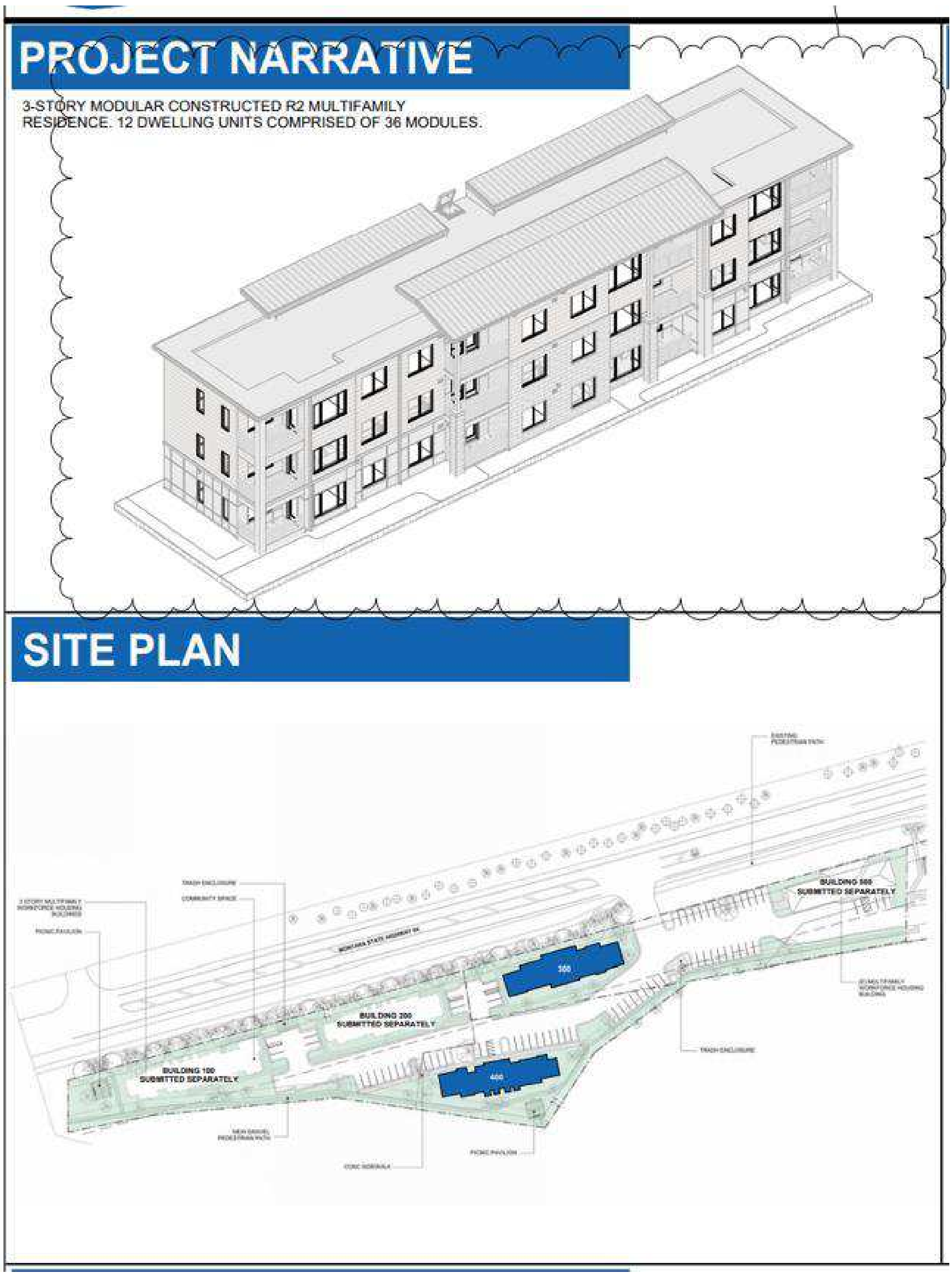

Figure 6 Buildings 300-400 (2 buildings)

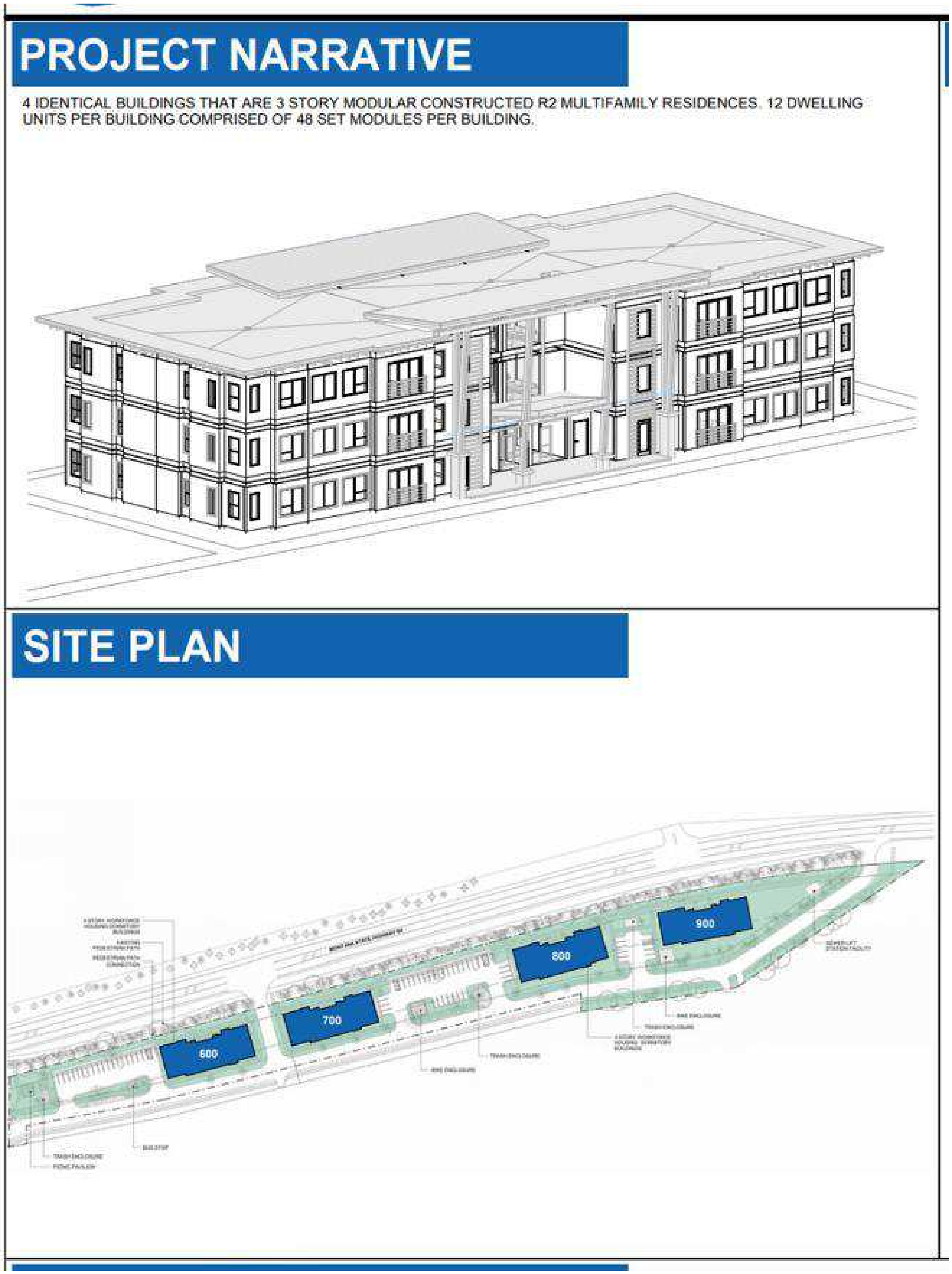

Figure 7 Buildings 600-900 (3 buildings – building 900 removed from study)

3.1.2 Traditional Site Built Project Characteristics

The site-built project was a four story, mixed-use building (Figure 8). The first floor was residential and retail with a slab floor and metal wall framing. The second floor was residential with a slab floor and wood wall framing. The third and fourth floors were residential with wood floor and wall framing. The residential floor area for the entire building was 192,201 SF. The retail floor area was 20,106 SF. There is a local ordinance that requires wood waste sorting during the construction period. Wood waste was sorted during the framing period. This project did not pursue green building certification such as LEED or Green Globes.

Figure 8 Site-built project - four story, mixed use (photo from project plans)

3.1.3 Comparison of Projects

Table 4 shows the project data side by side. The site built project was 4 stories with 192,000 SF floor area for residential and 20,000 SF floor area for retail. The modular project was 5 3-story buildings with a total of 82,000 SF floor area for residential and no retail space. The site-built project had a local ordinance requiring waste sorting, while the modular project did not. Both projects had onsite waste sorting, but the modular project only sorted wood waste for the factory portion of construction. Neither project was pursuing a green certification such as LEED or Green Globes, e.g..

Table 4 Comparison of Projects

	Modular	*Site Built*
Residential SF (floor)	81,679 (5 buildings)	192,201
Retail SF (floor)	0	20,106
Local ordinance requiring waste sorting?	No (factory and site)	Yes
Onsite Waste sorting?	Yes (factory) No (site)	Yes
Green certification (LEED, Green Globes, e.g.)	No	No

3.2 Quantitative Data Collection: Waste Measurement

Wood waste was weighed by the hauler upon disposal and data was provided from the contractor via waste disposal tickets measuring tons of wood waste. The contractor for each project has also provided the project plans. From the project plans, the square footage of wood-framed walls and floors were measured for each project, using On-Screen Takeoff (OST). Once the wood framing area was determined for each project, waste collection data from each project was associated with the project wood framing area. Using pounds of waste per square foot (SF) of wood-framed walls, floors, and ceilings, I compared the waste generated by the two projects (USGBC, 2019).

The most commonly used method of estimating construction waste is area-based calculation (Wu et al., 2014). In this method, the total construction floor area is multiplied by the waste generation rate (measured in lbs/SF or kg/m^2). Previous studies compared waste in traditional site-built construction and offsite volumetric modular construction applied waste rates derived through a literature review (Loizou et al., 2021). This method, while insightful, did not quantify measured waste of specific projects. My study sought to fill the research gap and directly measure construction waste in each construction method.

To create a more accurate wood waste rate, I quantified the wall framing square footage of each project using On-Screen Takeoff (OST). Next, I quantified the square footage of wood floor space using OST. For the modular project, I also quantified the ceiling square footage because the floor and ceiling are not shared, as they are in traditional construction. I calculated pounds per square footage of walls and floors (and ceilings for the modular project) because quantifying the walls seemed particularly important for comparing multi-family projects. The quantity of walls in residential units varies and was expected to be a more accurate measurement for comparison than floor square footage alone.

The primary source for data in this study was the waste tickets from both projects that showed the wood waste diverted from the landfill. For the modular project, the wood waste was quantified by dumpster removal trips (Figure 9). The invoice is from the landscape company/ wood recycler. The invoice date was the date of hauling, which I cross-referenced with the framing dates, provided by the modular contractor. There was one waste ticket with an extra disposal charge, which I confirmed was due to contamination of the materials (non-wood items mixed in with the wood waste).

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INVOICE

BILL TO

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SHIP TO

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INVOICE # 2023-2928
DATE 07/31/2023
DUE DATE 08/15/2023
TERMS 15th

P.O. NUMBER
209155

ACTIVITY	QTY	RATE	AMOUNT
Roll-Offs:30 yd Serviced - Boise 30 yard Roll-Off Box	1	400.00	400.00

SUBTOTAL	400.00
TAX	0.00
TOTAL	400.00
BALANCE DUE	**$400.00**

Figure 9 Modular waste ticket

For the site-built project, wood waste was quantified by tons per 30-yard dumpster (Figure 10). The waste report provided by the contractor included haul date, which I cross-referenced with the framing dates provided by the contractor. I only included wood waste hauled during the framing period in our calculations. The report also included container size (30 yard) and confirms the material (wood). The tonnage was reported by the hauler. The post-collection site shows where the wood waste was taken. “Ewings” is a landscaping company/ wood recycler. “North Weld” is a landfill, which I confirmed does not recycle wood waste.

[redacted]

Tonnage Report

Container ID#	Haul Date	Disposal Arrival Time	Container Size	Material	Notes	Tonnage	Post Collection Site	Requestor
64234525400000103	09/21/2022	11:59	30	Wood		2.50	North Weld	[redacted]
64234525400000103	10/17/2022	10:56	30	Wood		1.76	North Weld	[redacted]
64234525400000103	10/27/2022	10:49	30	Wood		1.95	Ewings	[redacted]
64234525400000103	11/18/2022	10:34	30	Wood		2.97	North Weld	[redacted]
64234525400000103	12/07/2022	16:50	30	Wood		3.04	North Weld	[redacted]
64234525400000104	12/20/2022	10:40	30	Wood		4.26	North Weld	[redacted]
64234525400000103	12/20/2022	11:39	30	Wood		2.91	North Weld	[redacted]
64234525400000104	12/30/2022	11:20	30	Wood		3.50	Ewings	[redacted]
64234525400000103	12/30/2022	9:51	30	Wood		3.59	North Weld	[redacted]
64234525400000103	01/09/2023	14:09	30	Wood		3.76	North Weld	[redacted]
64234525400000103	01/13/2023	14:12	30	Wood		4.87	North Weld	[redacted]
64234525400000103	01/18/2023	9:25	30	Wood		2.23	North Weld	[redacted]
64234525400000103	01/19/2023	12:32	30	Wood		1.00	Ewings	[redacted]
64234525400000103	01/25/2023	15:18	30	Wood		4.71	North Weld	[redacted]
64234525400000103	02/10/2023	16:21	30	Wood		4.30	North Weld	[redacted]
					Total Tonnage	47.35		

Figure 10 Site Built waste report.

3.3 Qualitative Data Collection: Site Observation

For the traditional, site-built project, site visits were conducted in March and July. The purpose of both visits was to observe the waste management practices during the framing period. Tours were scheduled with the Project Manager in advance and I was escorted during my site tour. The March tour lasted roughly two hours, I spoke mostly to the Project Manager and had opportunity to speak to the carpenters and the Owner's Representative briefly. The July follow-up tour was less than an hour and I only interacted with the Project Manager.

For the volumetric modular project, site visits were conducted in March and August. The purpose of the March visit was to observe the manufacturing environment and waste sorting processes. The site tour of the modular manufacturing facility was scheduled in advance and lasted for a full day. I was given a tour by the Marketing Director, then was allowed to walk around the facility unsupervised. I had informal conversations with the Marketing Director, Project Manager, and the CEO of the modular manufacturer.

The purpose of the August visit was to observe the onsite construction environment for the modular project. This one-day visit was planned in advance to coincide with the setting of the modular units. I was mostly unsupervised on-site and had informal conversations with the Project Manager from the modular company, the Superintendent from the on-site construction company, a few of the tradespeople, and the developer for the project.

CHAPTER 4: RESULTS

I observed a higher rate of waste aversion in offsite volumetric construction than in site-built construction. The controlled environment that existed in the off-site project created a lower barrier to waste reduction than for site-built construction. The data from the waste tickets and the observations from the site visits both provided evidence to substantiate this finding.

4.1 Observations of Traditional, Site Built Construction Waste Management

During a site visit in March 2023, framing was 66% complete, based on contractor reporting. I observed relatively large volumes of wood waste on the site-built project, which were sorted and intended for landfill diversion. Figure 11 shows wood framing on the third level. Wood waste was collected on palettes and moved down to the wood waste receptacle on ground level. There was limited reuse of wood scraps. I was told that it was usually easier to cut a new piece in situ, rather than go find an appropriately sized scrap in a different part of the project. In site-built construction, I was told, this method is more cost effective. In Figure 12, I observed a relatively high level of contamination in the wood waste receptacle (bottom of photo). I observed that the landfill dumpster (at top) and the wood waste dumpster (at bottom) were difficult to distinguish from above. Both were the same size and color. At street level, the wood waste receptacle had a hand-painted sign that said “WOOD” but this could not be identified from above.

Figure 11 Wood framing waste on site-built project (March 2023).

Figure 12 Waste sorting on site-built project (March 2023).

During the site visit in July 2023, wood framing was 100% complete, according to contractor reporting. I observed wood materials in the landfill dumpster, and the project was no longer source-separating wood (Figure 13). I observed wood framing waste on the fourth floor (Figure 14, Figure 15).

Figure 13 Wood waste in landfill dumpster (July 2023).

Figure 14 Wood waste on 4th floor (July 2023).

Figure 15 Wood and packaging waste on 4th floor exterior (July 2023)

4.2 Observations of Offsite, Volumetric Construction Waste Management

I observed controlled waste management practices at the modular manufacturing site in March 2023. During the observation period, Buildings 300 and 400 were complete, and Building 600 was approximately 50% complete. Buildings 700, 800, and 900 had not yet started construction. Waste receptacles were placed in convenient locations (Figure 16), near the wood framing workstations. Scraps that were too small for re-use were taken to a 30-yard dumpster, which was then hauled to a landscape materials company, where the construction wood waste was ground into bedding for livestock. The wood receptacles were labeled, and the 30-yard dumpster for wood recycling was easy to distinguish from the landfill 30-yard dumpster (Figure 18). Large wood scraps could be repurposed within the project (Figure 17). Larger plywood pieces were cut into strips and used for securing the plastic wrap material on the modular units when prepared for transport. I observed that waste sorting and reuse was relatively easy in the factory environment.

Figure 16 Wood waste receptacle in the modular factory (March 2023).

Figure 17 Plywood scraps are collected to be repurposed within the project (March 2023).

Figure 18 30-yard dumpster for wood waste (March 2023).

4.3 Observations of Onsite Installation of Volumetric Construction Waste Management

I observed the modular set for building 700 in August 2023. By this point, buildings 300, 400, and 600 had been placed, building 800 was ready, and building 900 was on hold until Spring 2024. I observed onsite framing activity in crawl spaces (buildings 300 and 400) and basements (buildings 600, 700, 800) (Figure 19). Within the buildings, there was some additional wood construction, namely stairs and some site-built walls (Figure 20, Figure 21). The site construction phase of the modular project appeared similar in waste efficiency as the traditional site-built project (Figure 22). This is a qualitative observation because wood waste was not separated onsite and wood waste was not quantified.

Figure 19 Building 700, unquantified wood framing in basement and crawl space.

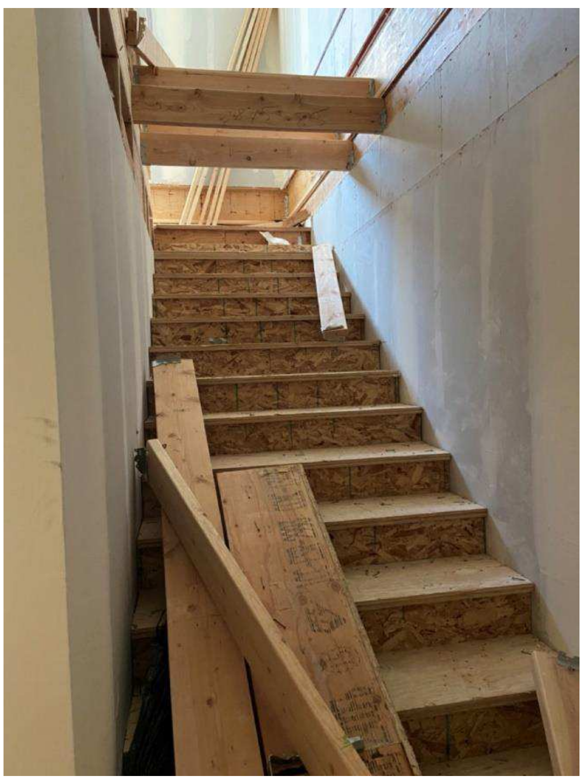

Figure 20 Building 600, onsite wood construction - wood stairs.

Figure 21 Unquantified wood waste - interior wall required for transport, will be removed.

Figure 22 Onsite wood waste, not quantified, not diverted from landfill.

4.4 Quantitative Results

The contractors for each project provided architectural drawings, framing dates, and waste tickets. I used On-Screen Takeoff (OST) to measure the wood framed walls and floors for each project. For the modular project, I also included the ceiling square footage because each completed module includes a floor and a ceiling. For the modular project, the wall area was 223,008 SF and the combined floor and ceiling area was 163,358 SF for five buildings (building 900 was excluded). For the site built project, the wall area was 320,617 SF for levels 2-4 and the floor area was 102,020 SF for levels 3 and 4 (level 2 was concrete slab). Level 1 had metal framed walls and concrete slab floor.

For the modular project, the wood waste was quantified by dumpster removal trips (Figure 9). For the site built project, wood waste was quantified by tons per 30 yard dumpster

(Figure 10). I used the average tons per 30 yard dumpster from the site built project (3.67 tons/30 yards) and the conversion rate for C&D waste "wood scrap, loose" from the California Integrated Waste Management Board (4.94 tons/30 yards) (CIWMB, n.d.) to generate an estimated range for the weight of the modular wood waste (Figure 23).

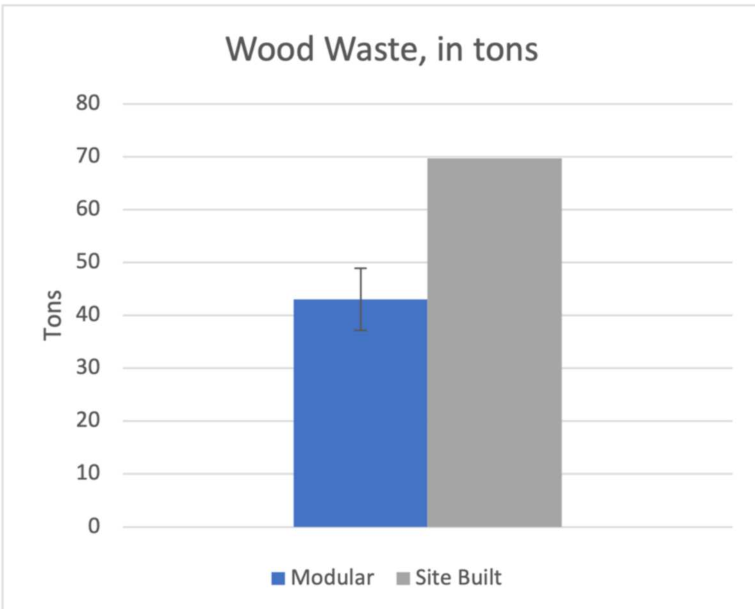

Figure 23 Measured wood waste, tons

The modular project was constructed in the factory during the period of February 2023 to June 2023. During that period, 10 30-yard dumpsters were hauled to the recycler. The recycler did not weigh the waste, so I estimated that .1900 - .2557 lbs/SF of wood waste was generated on the project.

Wood framing for the site-built project occurred during the period of December 2022 through April 2023. During that period, 19 30-yard dumpsters of wood waste were removed from the site, totaling 69.66 tons of waste, which equals .3296 lbs/SF of wood waste (Table 5).

Table 5 Wood Waste Comparison Table

	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 Wood Framing (SF) (Walls & Floors)	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

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CHAPTER 5: CONCLUSION

5.1 Summary of Results

Important concepts in CEBE include using waste as a resource and designing out waste. I sought to compare the wood framing waste generated in two construction methods: volumetric modular and traditional site-built. I identified wood framed multi-family projects that were source-separating wood waste but not seeking a "green" certification (LEED, Green Globes, e.g.). I measured the square footage of wood framed walls, floors, and ceilings (modular only) using OST. Framing dates and waste tickets were provided by the contractors for both projects. The modular project provided pick-up dates for the 30 yard dumpsters but was not weighed. The site-built project provided pick-up dates and weight of each load. I used this information to determine an estimated weight range for the modular project. The wood waste produced on the modular project was between 0.1900 lb/SF and 0.2557 lb/SF. The wood waste produced on the site-built project was 0.3296 lb/SF. Overall, the modular project produced 20-33 fewer tons of wood than the traditional site-built project. Which is approximately 10 -16.5 tons of sequestered CO_2 per year, according to the methods from Toochi (2018).

This study sought to answer the overarching research question: Is less wood-framing waste produced on the volumetric modular multi-family case project than on the traditional, site-built multi-family case project? The null hypothesis stated that the wood waste produced by the modular case project is greater than or equal to the wood waste produced by the traditional, site-built case project. The alternative hypothesis stated that the wood waste produced by the modular case project is less than the wood waste produced by the traditional, site-built case project.

$$H_0: \text{Wood Waste}_{\mathit{Modular1}} \geq \text{Wood Waste}_{\mathit{Site\text{-}Built1}}$$

$$H_1: \text{Wood Waste}_{\mathit{Modular1}} < \text{Wood Waste}_{\mathit{Site\text{-}Built1}}$$

This study demonstrates that there is evidence to reject the null hypothesis. In this study, the volumetric modular case project generated 20-33 fewer tons of wood framing waste than traditional site-built case project. It is an important step in the growing body of work in circular economics in the built environment and the sustainability of modular construction. Due to the nature of convenience sampling, and the different waste management practices for both modular and traditional construction firms, this study will not be able to be generalized. However, the insights gleaned could be used by practitioners to strengthen waste management practices and could be used to develop future studies related to waste diversion in modular, off-site construction and traditional, site-built construction.

5.2 Limitations and Lessons Learned

As with all case studies, the primary limitation of this study is that the results cannot be applied generally to all construction projects. There is considerable variation in the design of modular factories and the waste management practices therein. Similarly, traditional site-built contractors also vary in their waste management practices. In addition, there were several project-specific limitations to this study:

5.2.1 Limitations for the Volumetric Modular Project

This study only quantified the wood framing waste during the off-site construction phase. There was wood-framing work that occurred onsite, and the waste was not measured. I had access to the modular construction documents, and not the onsite construction documents. Thus, I was unaware that there are crawlspaces in buildings 300 and 400 and basements in buildings 600-900 until the site visit (see Figure 24). This could have been resolved by requesting access to the onsite construction documents in advance. Even so, while the developer for this project was willing to grant access to us, he was not willing to spend extra money to support this research. There was no separation of wood waste during the onsite construction phase of this project.

Figure 24 Observed onsite wood construction and waste

As previously discussed, quantifying the wood waste during the offsite construction phase was fairly straightforward because the factory layout made it easy to place collection bins at the wood construction stations. In addition, factory processes made it possible to use smaller wood pieces in other parts of the project. During the observation in March, it appeared that most of the wood waste was either planned for re-use or in the designated wood recycling bins. Unfortunately, the wood recycler does not weigh the wood they collect. It's very likely that the weights of each collection varied, as it did with the site-built construction project. As such, I estimated a range within which the actual lbs/SF of factory wood waste should reside.

Another limitation for this study is the nature of the assembly line means that there was overlap in the factory with our study project and projects before and after. It's not possible to say with certainty what percentage of the first and last wood recycling bins belong to each project. More importantly, there was another project inserted during the factory construction of building 900. I chose to eliminate building 900 from the study to reduce the difficulty of attributing the wood waste to the appropriate project. The construction of building 900 was also placed on hold in Montana until Spring 2024. Even with these limitations, I believe this study is a useful starting point for future research that seeks to quantify wood waste in construction.

5.2.2 Limitations for the Traditional Site Built Construction Project

There were three major limitations to the data collection for the traditional site-built construction project. First, the wood waste sorting onsite was inconsistent. During both site visits, I observed wood mixed in with the regular waste. Second, only about 34% of the wood waste was diverted from the landfill during the study period. It was speculated that the wood dumpsters were contaminated with other waste and would not have been accepted at the recycler, thus the weight of the dumpsters that went to the landfills were unlikely to be 100% wood. Figure 25 demonstrates that using tons of wood waste from the waste tickets introduces uncertainty into the data. 10% contamination represents 90% wood with 10% other waste materials. If true, this would have reduced the total wood waste by about 4.6 tons. From site observations, the true contamination was more likely 50% or above. If true, the total wood waste would be reduced by about 23 tons.

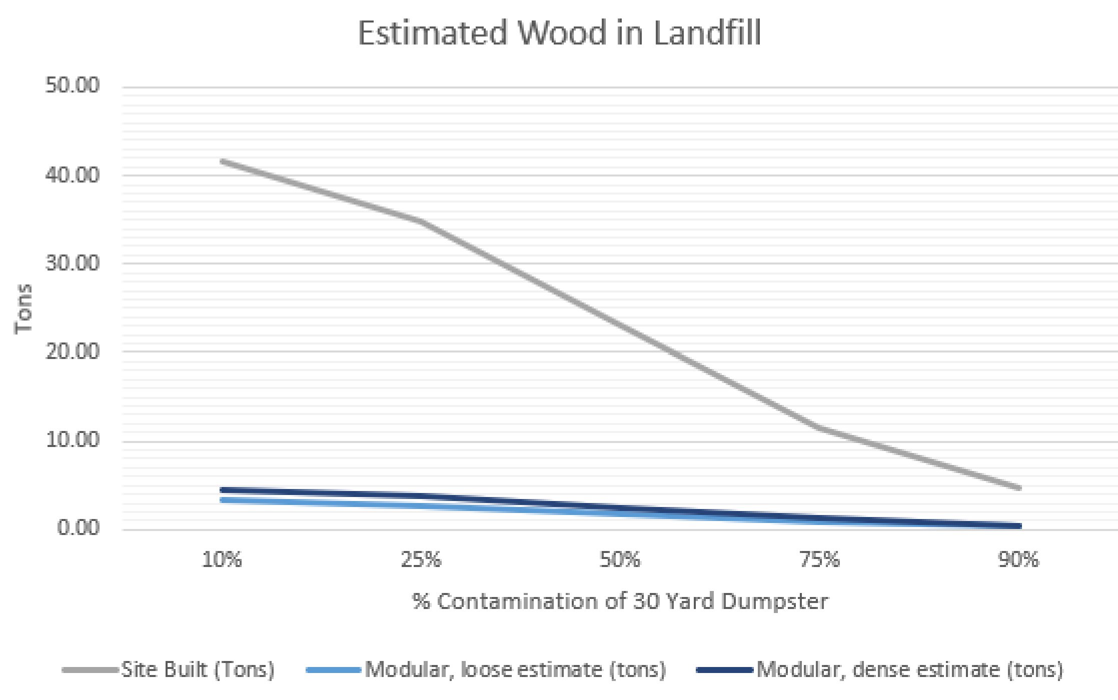

Figure 25 Estimated wood in landfill for site-built and modular projects.

Another way to interpret Figure 25 is to note that, regardless of contamination percentage, offsite modular projects divert more wood waste from the landfill. At an estimated 50% contamination rate, about 23 tons of wood waste went to the landfill for the site-built project. This is well above modular's 2.5 tons of potential wood in the landfill, densely packed at 50% contamination.

Third, the wood framing dates from the contractor do not align with the work observed during site visits. I observed wood framing activities and wood waste during the July site visit but, according to the contractor, framing was completed on April 20th. The contractor also stopped wood recycling at the end of May, possibly before framing was completed. In addition, the measured wood waste for Level 3 was roughly half of the waste for levels 2 and 4, indicating that there may have been an undercount of wood waste on this level. In this study, I used the framing dates given by the contractor and the measured hauling weights to determine the lbs/SF of wood waste for the project. I also established a range of wood waste (as with the modular project), using the average tons/30 yard dumpster (3.67 tons/30 yards from this project) as the low estimate and the California Integrated Waste Management Board's estimate for wood scraps, loose (4.94 tons/ 30 yards) (CIWMB, n.d.) as the high estimate.

5.3 Discussion & Significance of the Study

The primary limitation of this methodology is that it is not generalizable. Modular construction firms vary in their waste management practices, as do traditional, site-built construction firms. However, I believe that the results of this study will be useful to practitioners who may wish to employ some of the waste separation techniques and researchers who may wish to expand and improve on this study.

Though there are significant limitations in this study that should be addressed in future studies, there is still evidence to suggest that offsite construction methods can reduce wood framing waste due to the controlled factory environment. While difficult to measure, waste aversion (i.e., using smaller pieces within the project, rather than disposing of them) is an important contribution to circular economy and can easily be part of the process in a factory environment where the wood construction is done at specific stations. Waste aversion is possible, but not as easy, in the site-built environment where the carpenters move and it would be tedious and time-consuming to move scraps for future use.

In addition, there was only one contaminated 30 yard dumpster for the modular project, compared to roughly 63% of 30 yard dumpsters contaminated on the site-built project (12 out of the 19 dumpsters went to landfill). This high rate of contamination for the site-built project could be due to many factors, including poor training, unclear signage, and a lack of priority of on-site sorting. However, it may be worth examining if the factory process contributes to the relatively higher level of wood waste diversion in offsite modular construction.

It is worth noting that, while there seems to be evidence of wood waste diversion in the factory environment, there is no noticeable difference onsite in waste management between the modular project and the site-built project. The savings come from the fact that the majority of wood construction in a volumetric modular project occurs in the factory environment.

5.4 Future Research

A useful next step would be to expand this comparative case study to include multiple modular projects and site-built projects. It would be important to be sure that all wood waste is being sorted and weighed. Different manufacturers and contractors have different waste management practices, so a larger sample size may offer data that is generalizable.

During the course of this research, I discovered that there are two additional multi-family buildings that are being constructed near the modular buildings. The developer for these buildings chose to have the wood-framed walls constructed off-site, and it would be interesting to see how the wood waste for this construction method compares to the volumetric modular project and the traditional site built project if the data is available.

In addition, one of the claims of the volumetric modular industry, particularly with multi-family construction, is that faster speed to market offsets the higher upfront costs of volumetric modular construction. As of this writing, none of the observed projects are complete, but a future study could compare construction costs, construction time, and revenues.

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APPENDIX 1 – MODULAR WASTE DATA TABLE

Modular Production Dates (Idaho)

	Date Online	Last Mod Offline	Overlap (days)	Production Days	Wood Removal Count
Building 300	2/10/2023	3/13/2023		31	4
Building 400	2/24/2023	3/24/2023	17	28	2
Building 600 (photos of production)	3/9/2023	4/19/2023	15	41	2
Building 700	4/3/2023	5/11/2023	16	38	3
Building 800	4/26/2023	6/8/2023	15	43	5
				Totals - Buildings 300-800 (with overlap)	16
				Waste removal overlap	6
				Total Wood Removal Trips (w/o overlap)	10

APPENDIX 2 – SITE-BUILT WASTE DATA

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

"Weld" is a landfill, "Ewings" is a landscaping company.

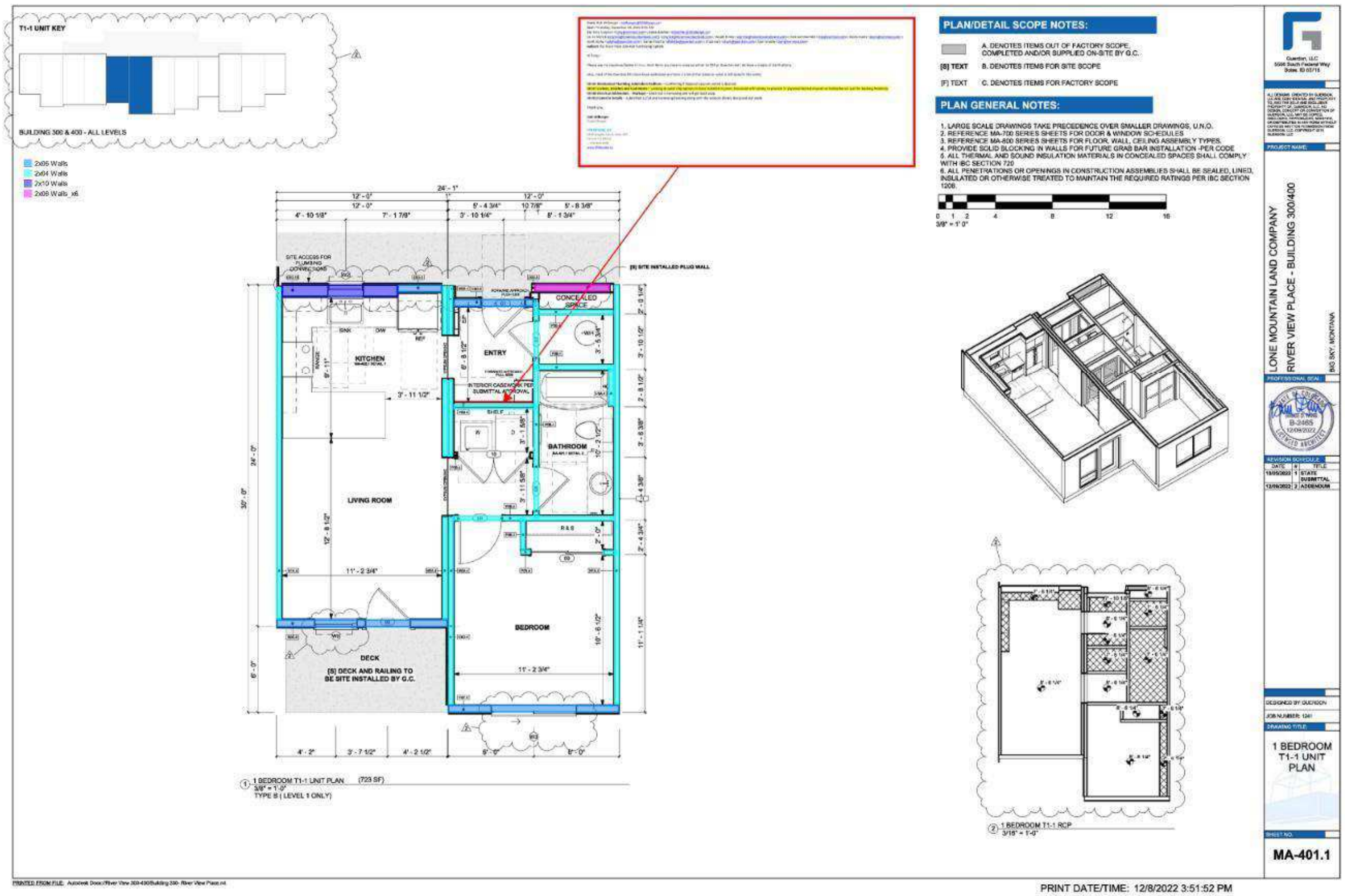
APPENDIX 3 – ESTIMATED WOOD IN LANDFILL DATA

Estimated Wood in Landfill			
Contamination (%)	Site Built (Tons)	Modular, loose estimate (tons)	Modular, dense estimate (tons)
10%	41.65	3.30	4.45
25%	34.71	2.75	3.71
50%	23.14	1.84	2.47
75%	11.57	0.92	1.24
90%	4.63	0.37	0.49

Data to support Figure 25.

APPENDIX 4 – MODULAR PROJECT OST DATA

Modular Walls – Buildings 300-400



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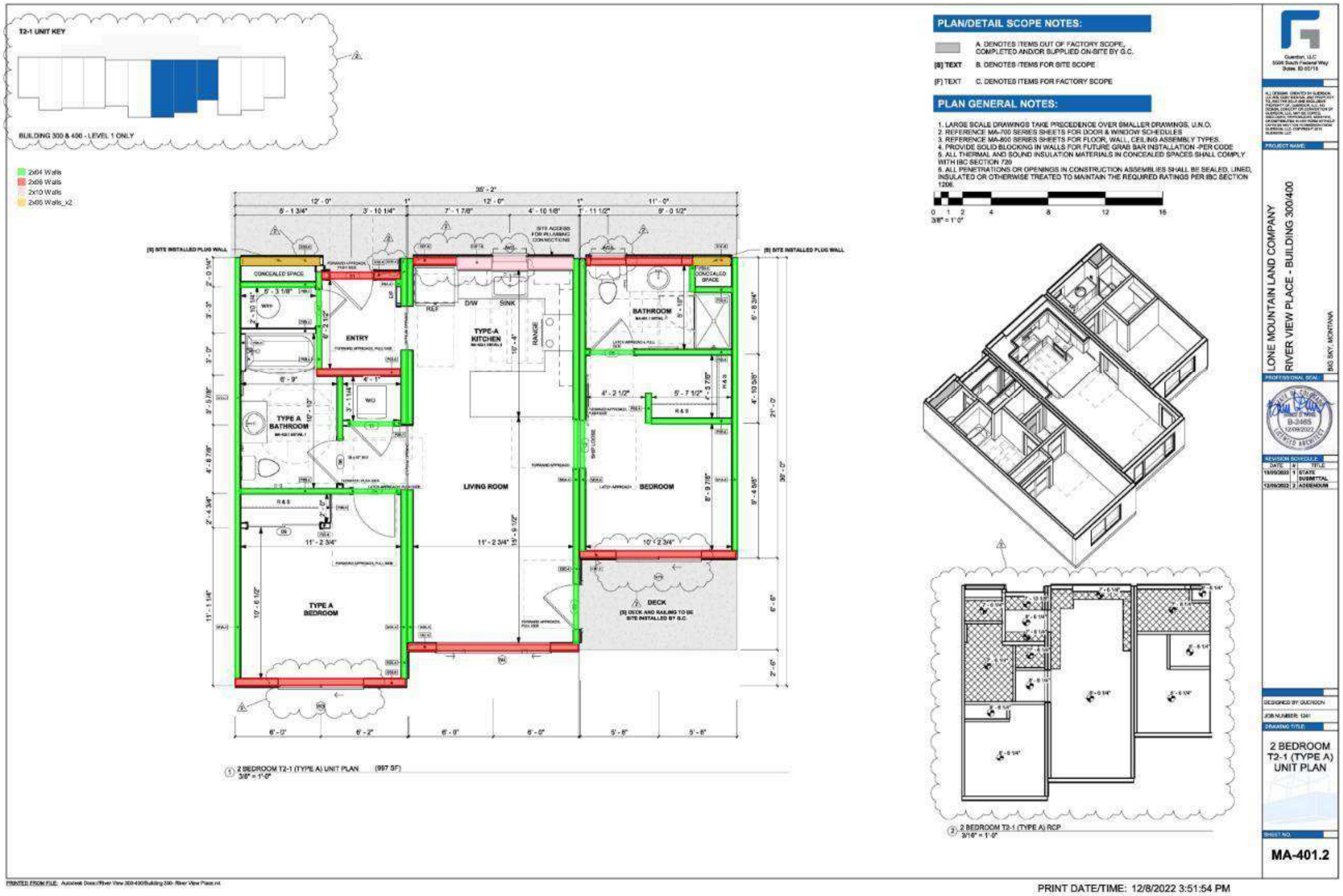

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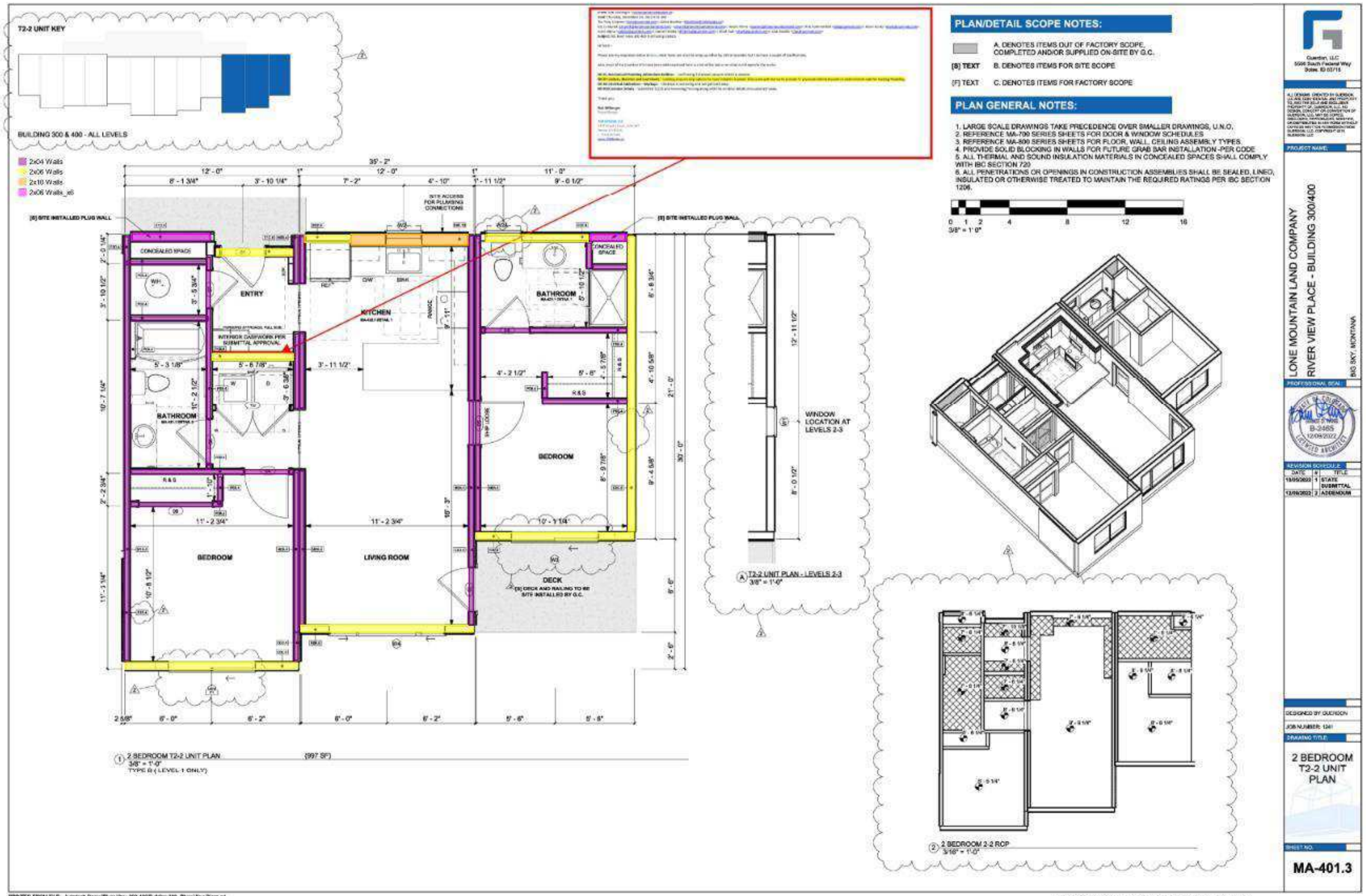

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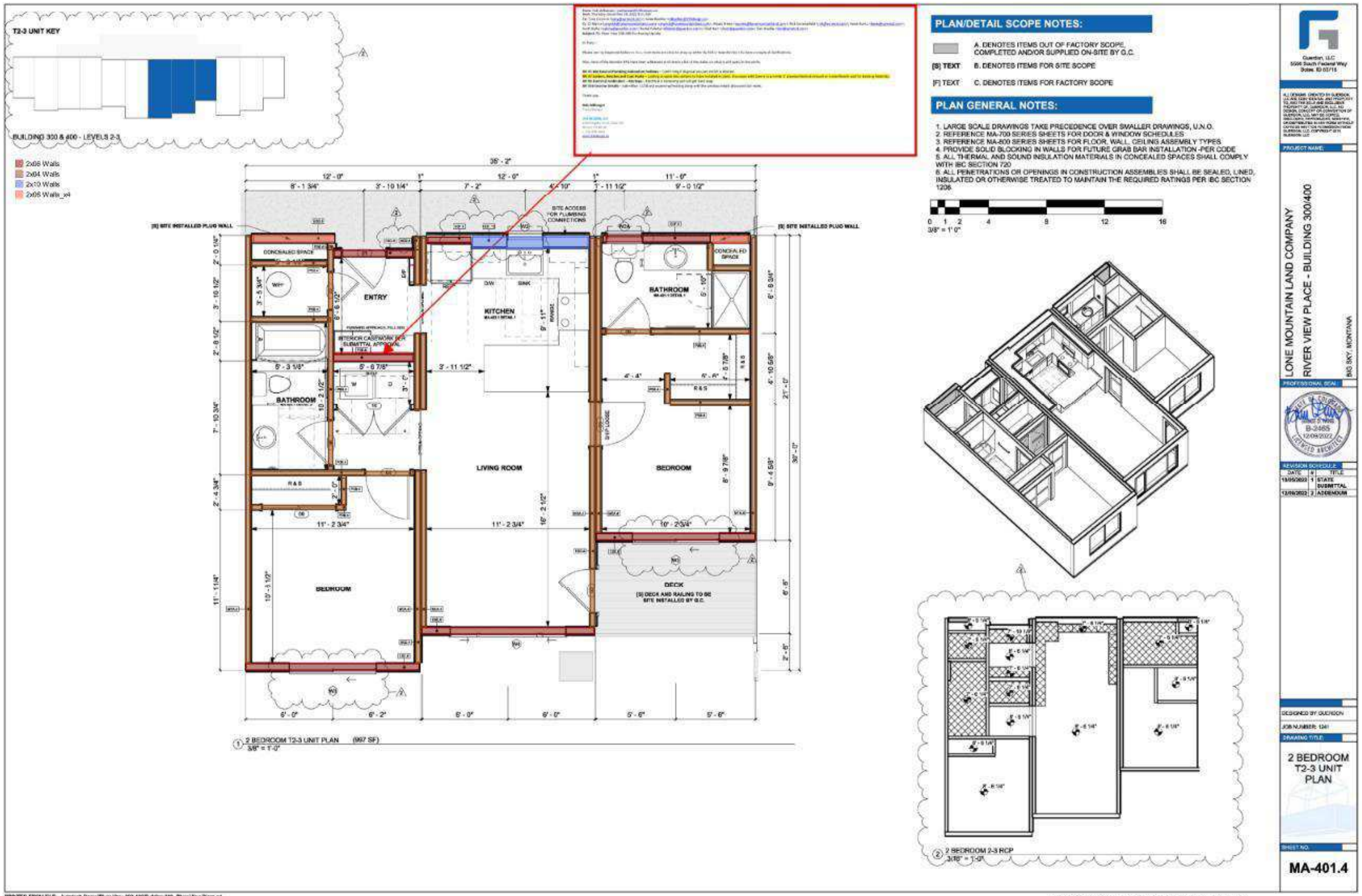

PRINTED FROM FILE: Autodesk Docs://River View 300-400/Building 300- River View Place.rvt

PRINT DATE/TIME: 12/8/2022 3:51:59 PM

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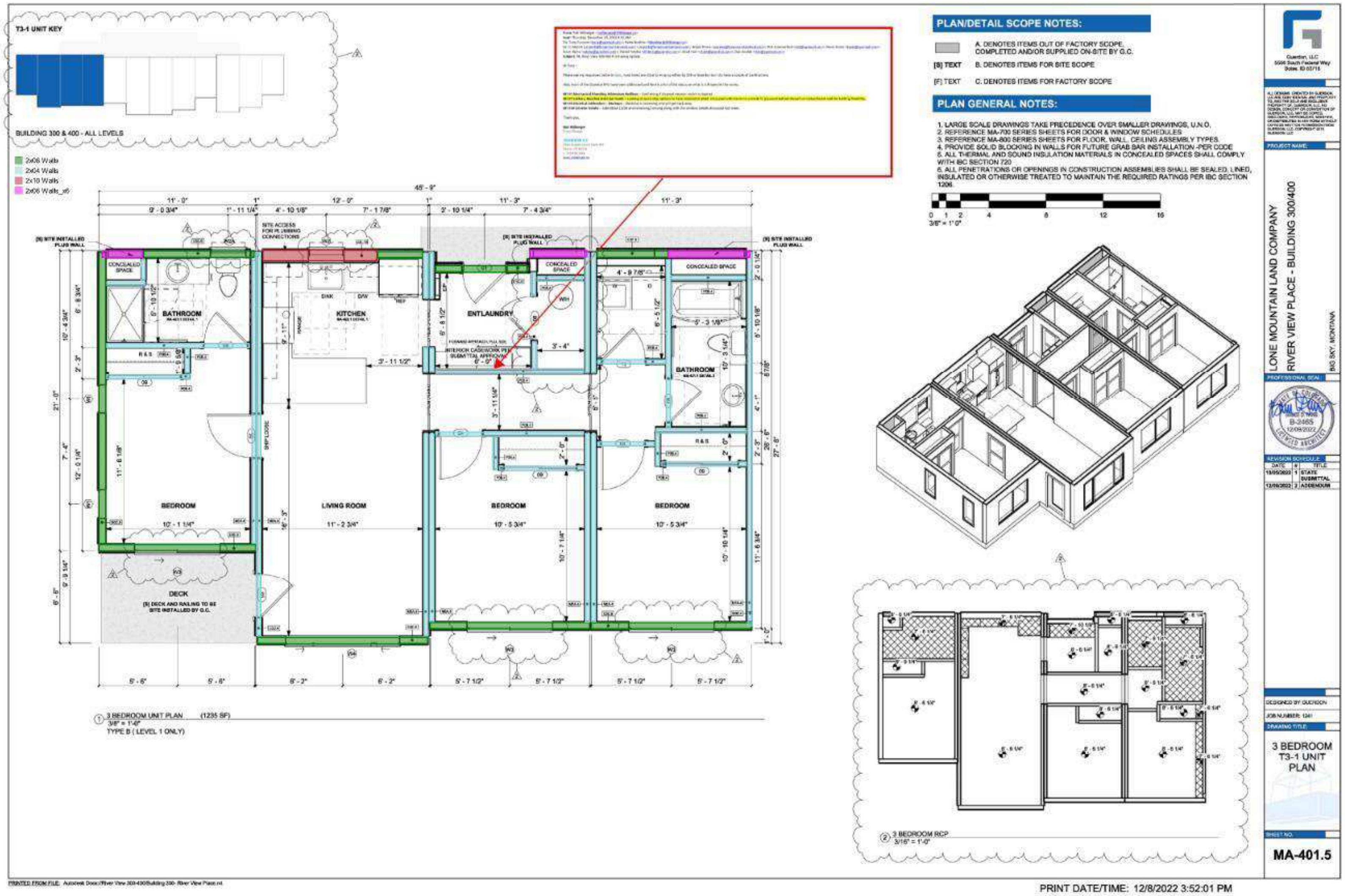
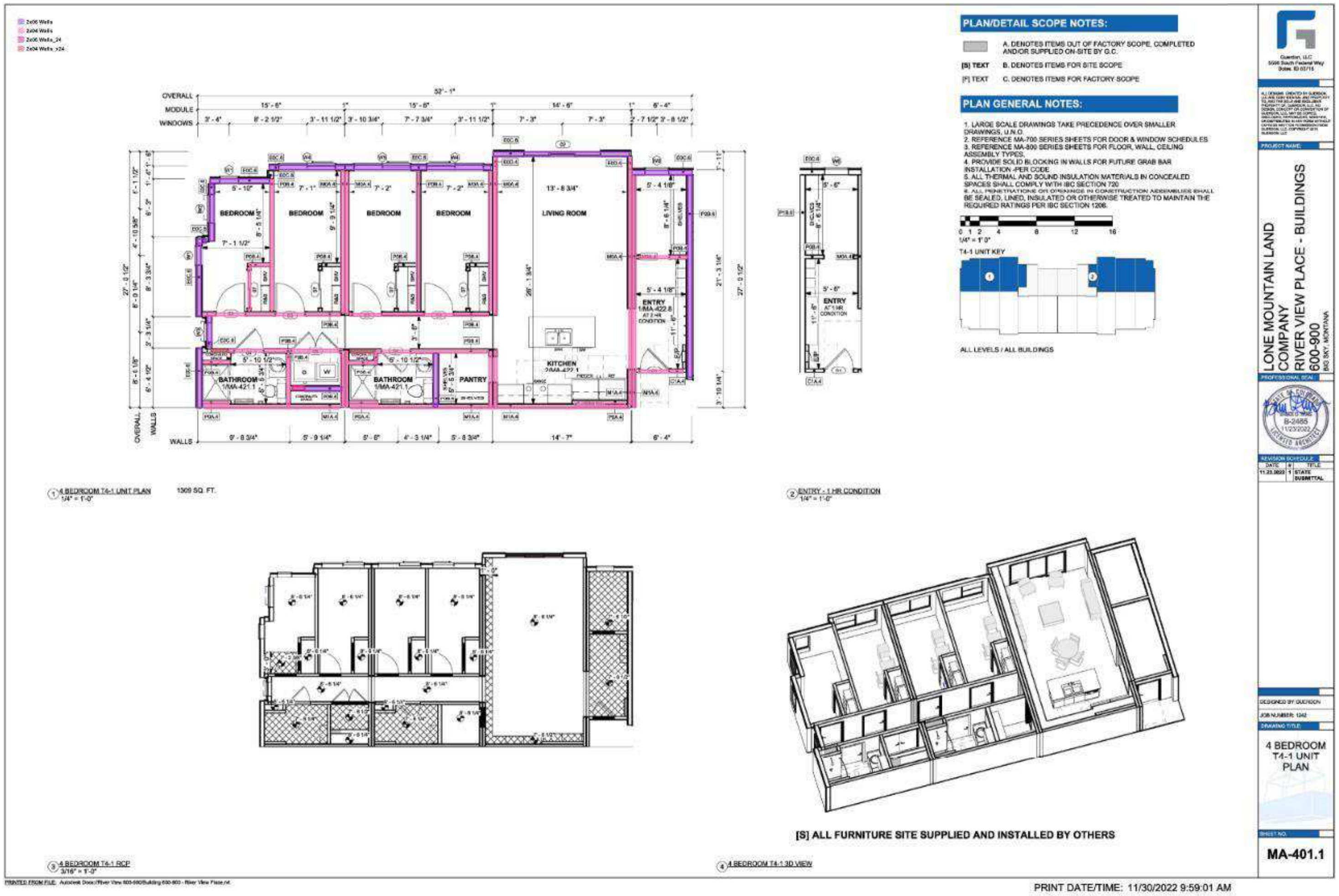


Riverview Place 300-400_Modular Architecture Addendum 1 (6).pdf (20) (30% of Scale); Takeoff in Active Area: All Areas; Riverview Place_Modular; Riverview Place_Modular; 8/25/2023 07:49 PM

Modular Walls – Buildings 600-900



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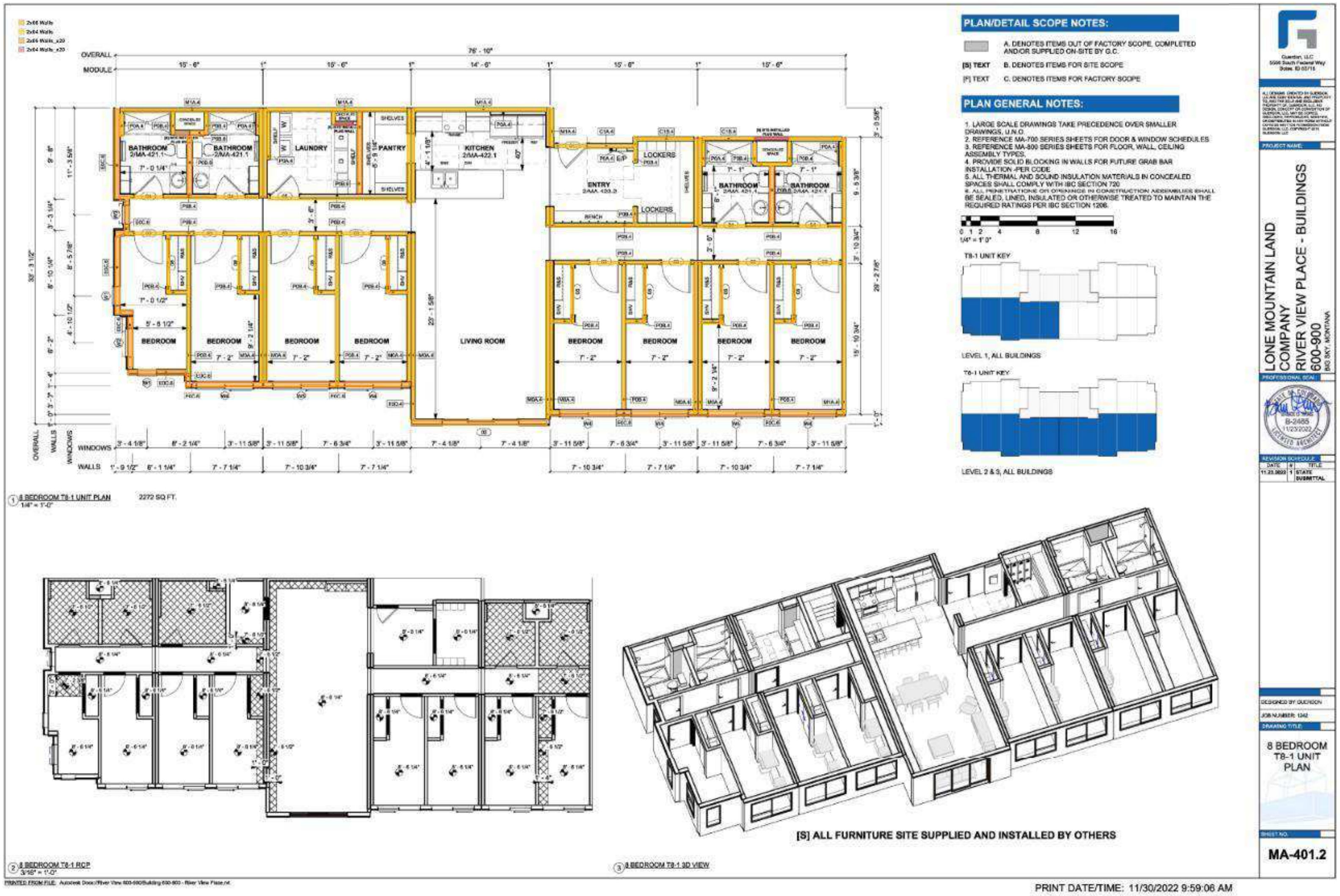
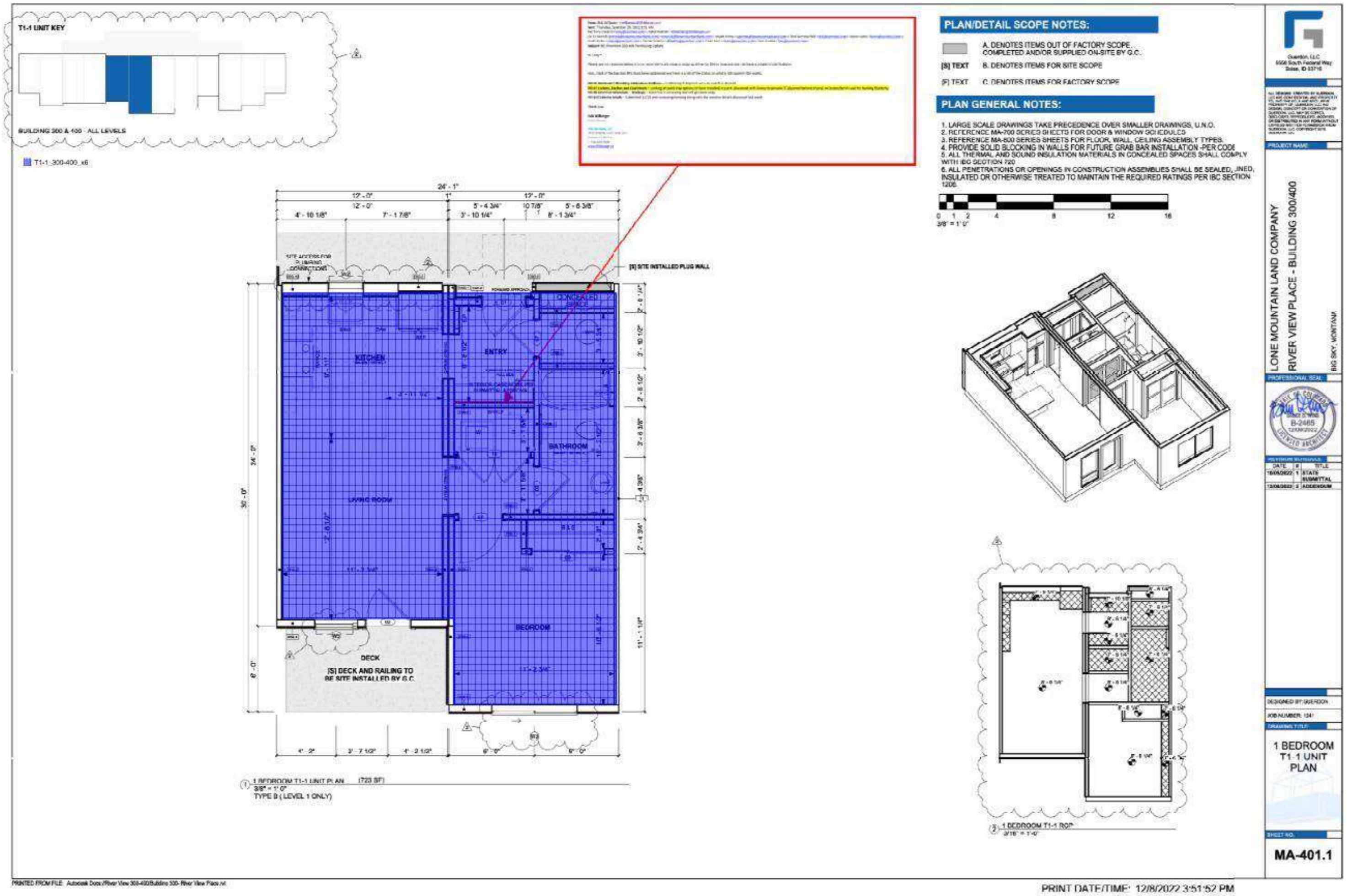


Riverview Place 600-900_Modular Architecture (4).pdf (19) (30% of Scale); Takeoff in Active Area: All Areas; Riverview Place_Modular; Riverview Place_Modular; 8/25/2023 07:49 PM

Riverview Place 600-900_Modular Architecture (4).pdf (20) (30% of Scale); Takeoff in Active Area: All Areas; Riverview Place_Modular; Riverview Place_Modular; 8/25/2023 07:49 PM

Modular Floors – Buildings 300-400



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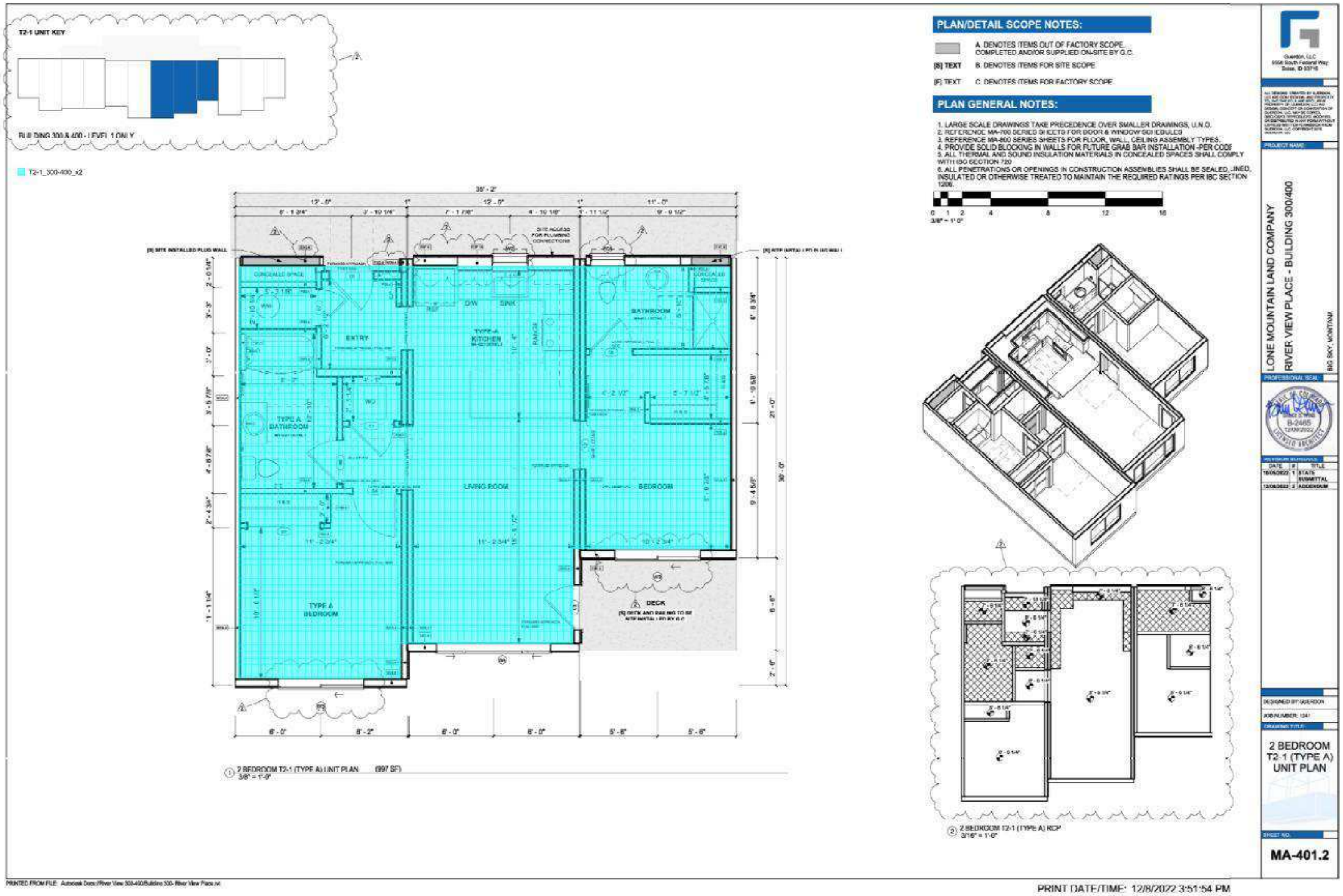

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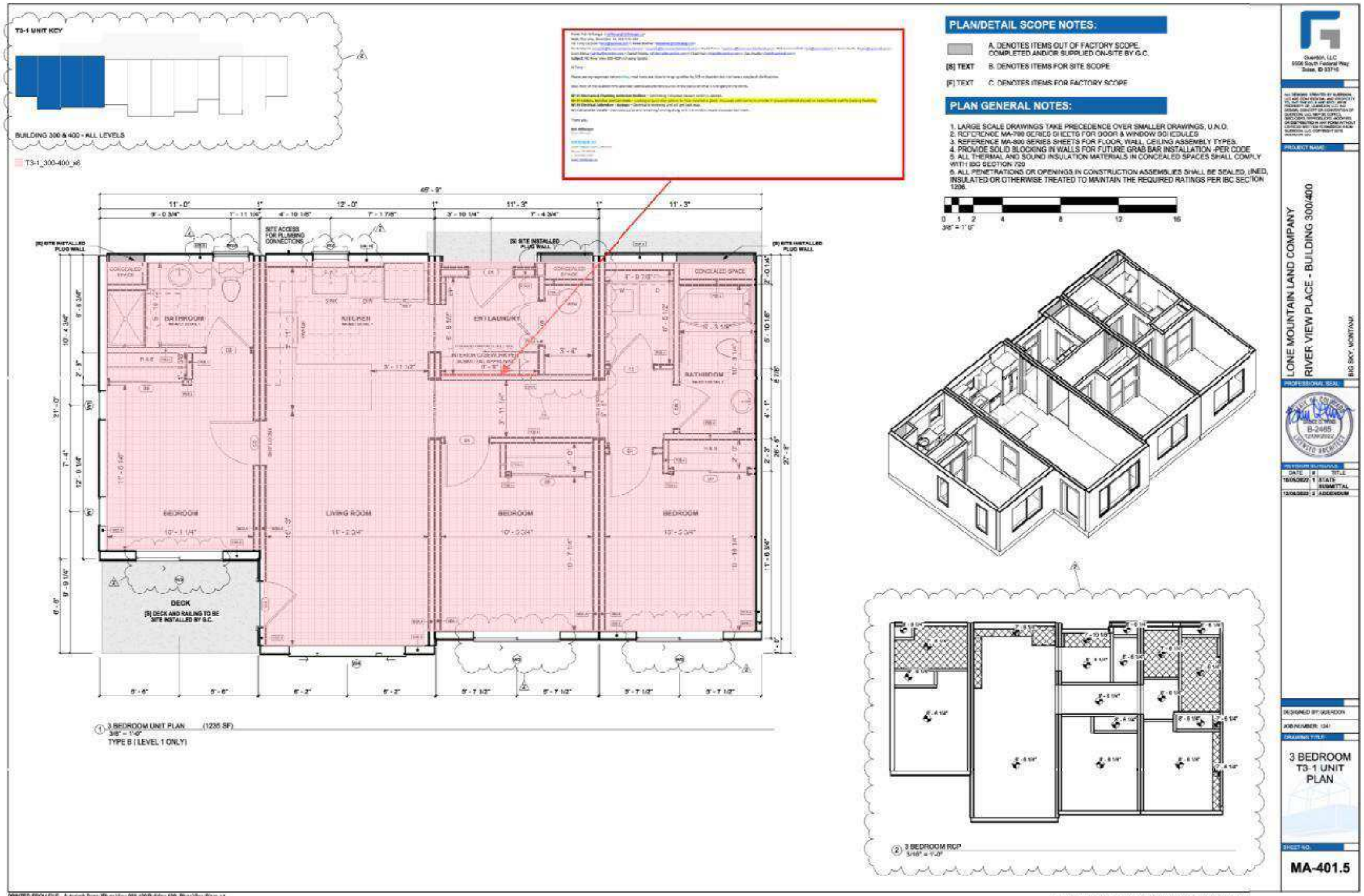

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Modular Floors – Buildings 600-900

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Riverview Place 600-900_Modular Architecture (4).pdf (20) (30% of Scale); Takeoff in Active Area: All Areas; Riverview Place_Modular; Riverview Place_Modular; 9/6/2023 12:07 PM

Modular OST Takeoff – All Buildings

Takeoff Tab

Riverview Place_Modular

Bid No. 1

No.	Name	Height	Area	Quantity1	UOM1	Quantity2	UOM2	Quantity3	UOM3
300-400 Floor SF									
18	T1-1_300-400_x6	0"	(unassigned)	604	SF	0		0	
33	T2-1_300-400_x2	0"	(unassigned)	862	SF	0		0	
34	T2-2_300-400_x6	0"	(unassigned)	861	SF	0		0	
35	T2-3_300-400_x4	0"	(unassigned)	869	SF	0		0	
36	T3-1_300-400_x6	0"	(unassigned)	1,090	SF	0		0	
600-900 Floor SF									
37	T4-1_600-900_x24	0"	(unassigned)	1,226	SF	0		0	
38	T8-1_600-900_x20	0"	(unassigned)	2,170	SF	0		0	
39	T8-2_600-900_x4	0"	(unassigned)	2,177	SF	0		0	
Site Installed Plug Walls_300-400									
29	2x06 Walls_x2 Multiply by 2 16" O.C.	8' 6.25"	(unassigned)	68	SF	31	CF	0	
30	2x06 Walls_x4 Multiply by 4 16" O.C.	8' 6.25"	(unassigned)	68	SF	31	CF	0	
28	2x06 Walls_x6 Multiply by 6 16" O.C.	8' 6.25"	(unassigned)	219	SF	100	CF	0	
Site Installed Plug Walls_600-900									
32	2x04 Walls_x20 Multiply by 20 16" O.C.	8' 6.25"	(unassigned)	45	SF	13	CF	0	
26	2x04 Walls_x24 Multiply by 24 16" O.C.	8' 6.25"	(unassigned)	36	SF	11	CF	0	
24	2x04 Walls_x4 Multiply by 4 16" O.C.	8' 6.25"	(unassigned)	33	SF	10	CF	0	
27	2x06 Walls_24 Multiply by 24 16" O.C.	8' 6.25"	(unassigned)	11	SF	5	CF	0	
31	2x06 Walls_x20 Multiply by 20 16" O.C.	8' 6.25"	(unassigned)	12	SF	6	CF	0	
25	2x06 Walls_x4 Multiply by 4 16" O.C.	8' 6.25"	(unassigned)	13	SF	6	CF	0	
T1-1_300-400_x6									
3	2x04 Walls Multiply by 6 16" O.C.	8' 6.25"	(unassigned)	1,190	SF	347	CF	0	
1	2x06 Walls Multiply by 6 16" O.C.	8' 6.25"	(unassigned)	279	SF	128	CF	0	
2	2x10 Walls Multiply by 6 16" O.C.	8' 6.25"	(unassigned)	69	SF	53	CF	0	

10/8/2023 11:35:10AM Page 1 of 3

Takeoff Tab

Riverview Place_Modular

Bid No. 1

No.	Name	Height	Area	Quantity1	UOM1	Quantity2	UOM2	Quantity3	UOM3
T2-1_300-400_x2									
4	2x04 Walls Multiply by 2 16" O.C.	8' 6.25"	(unassigned)	1,625	SF	474	CF	0	
5	2x06 Walls Multiply by 2 16" O.C.	8' 6.25"	(unassigned)	481	SF	221	CF	0	
6	2x10 Walls Multiply by 2 16" O.C.	8' 6.25"	(unassigned)	69	SF	53	CF	0	
T2-2_300-400_x6									
7	2x04 Walls Multiply by 6 16" O.C.	8' 6.25"	(unassigned)	1,565	SF	456	CF	0	
8	2x06 Walls Multiply by 6 16" O.C.	8' 6.25"	(unassigned)	649	SF	297	CF	0	
9	2x10 Walls Multiply by 6 16" O.C.	8' 6.25"	(unassigned)	69	SF	53	CF	0	
T2-3_300-400_x4									
10	2x04 Walls Multiply by 4 16" O.C.	8' 6.25"	(unassigned)	1,751	SF	511	CF	0	
11	2x06 Walls Multiply by 4 16" O.C.	8' 6.25"	(unassigned)	479	SF	220	CF	0	
12	2x10 Walls Multiply by 4 16" O.C.	8' 6.25"	(unassigned)	68	SF	53	CF	0	
T3-1_300-400_x6									
13	2x04 Walls Multiply by 6 16" O.C.	8' 6.25"	(unassigned)	2,141	SF	625	CF	0	
14	2x06 Walls Multiply by 6 16" O.C.	8' 6.25"	(unassigned)	750	SF	344	CF	0	
15	2x10 Walls Multiply by 6 16" O.C.	8' 6.25"	(unassigned)	68	SF	53	CF	0	
T4-1_600-900_x24									
16	2x04 Walls Multiply by 24 16" O.C.	8' 6.25"	(unassigned)	2,546	SF	743	CF	0	
17	2x06 Walls Multiply by 24 16" O.C.	8' 6.25"	(unassigned)	896	SF	411	CF	0	
T8-1_600-900_x20									
19	2x04 Walls Multiply by 20	8' 6.25"	(unassigned)	4,847	SF	1,414	CF	0	

Takeoff Tab

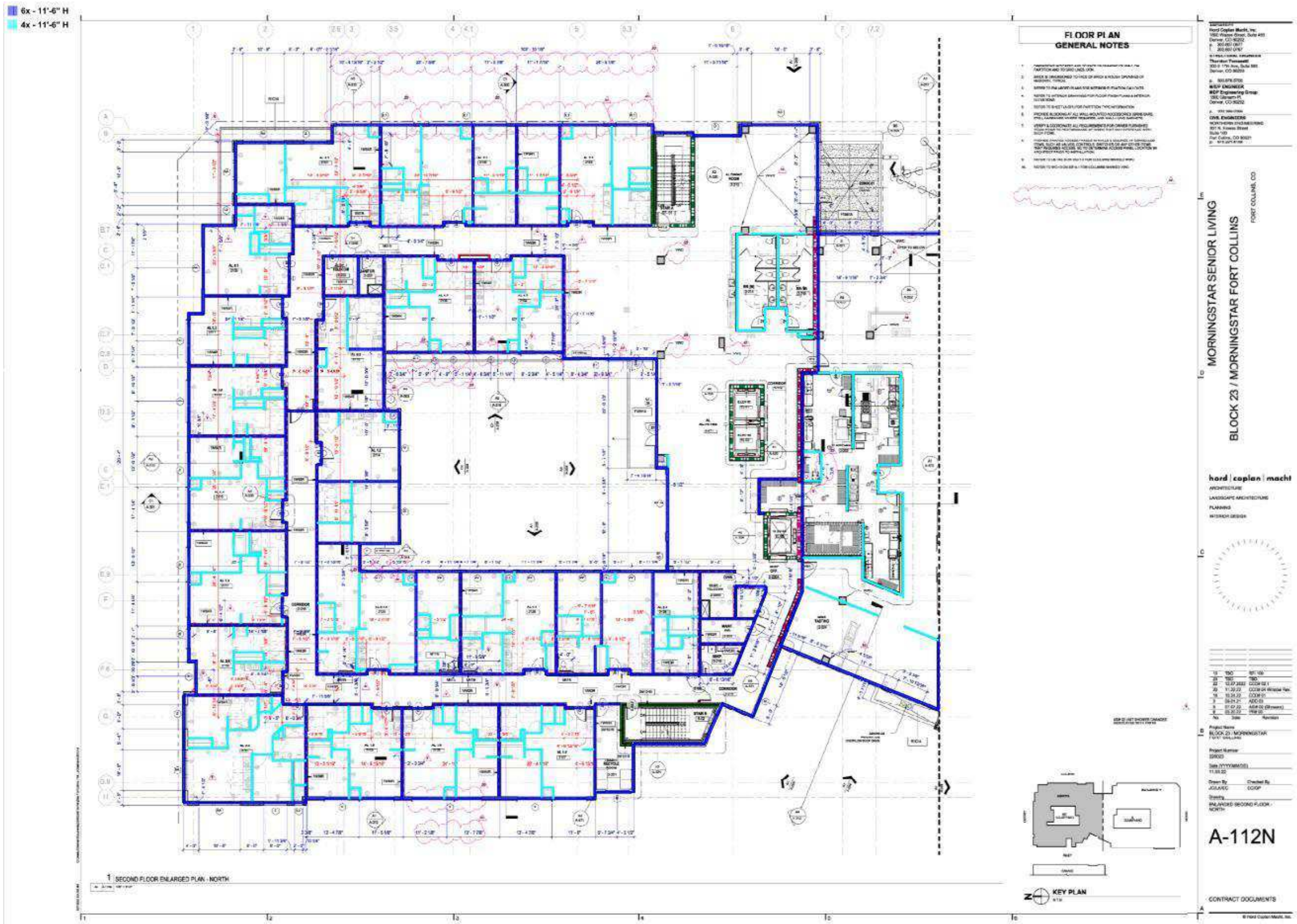
Riverview Place_Modular

Bid No. 1

No.	Name	Height	Area	Quantity1	UOM1	Quantity2	UOM2	Quantity3	UOM3
	16" O.C.								
20	2x06 Walls Multiply by 20 16" O.C.	8' 6.25"	(unassigned)	1,076	SF	493	CF	0	
T8-2_600-900_x4									
22	2x04 Walls Multiply by 4 16" O.C.	8' 6.25"	(unassigned)	4,922	SF	1,436	CF	0	
23	2x06 Walls Multiply by 4 16" O.C.	8' 6.25"	(unassigned)	1,073	SF	492	CF	0	

APPENDIX 5 – SITE BUILT PROJECT OST DATA

Site Built Walls – Level 2



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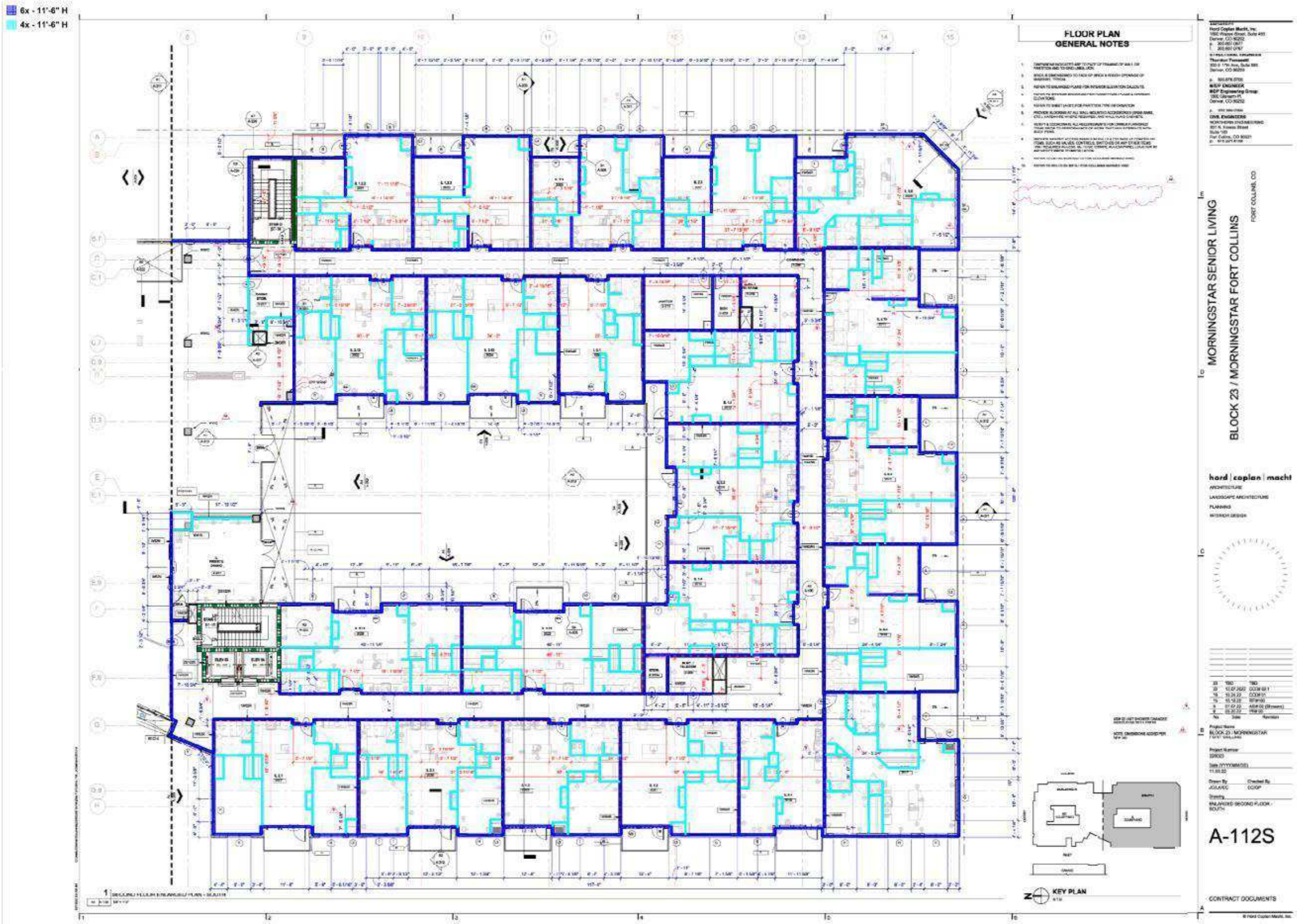

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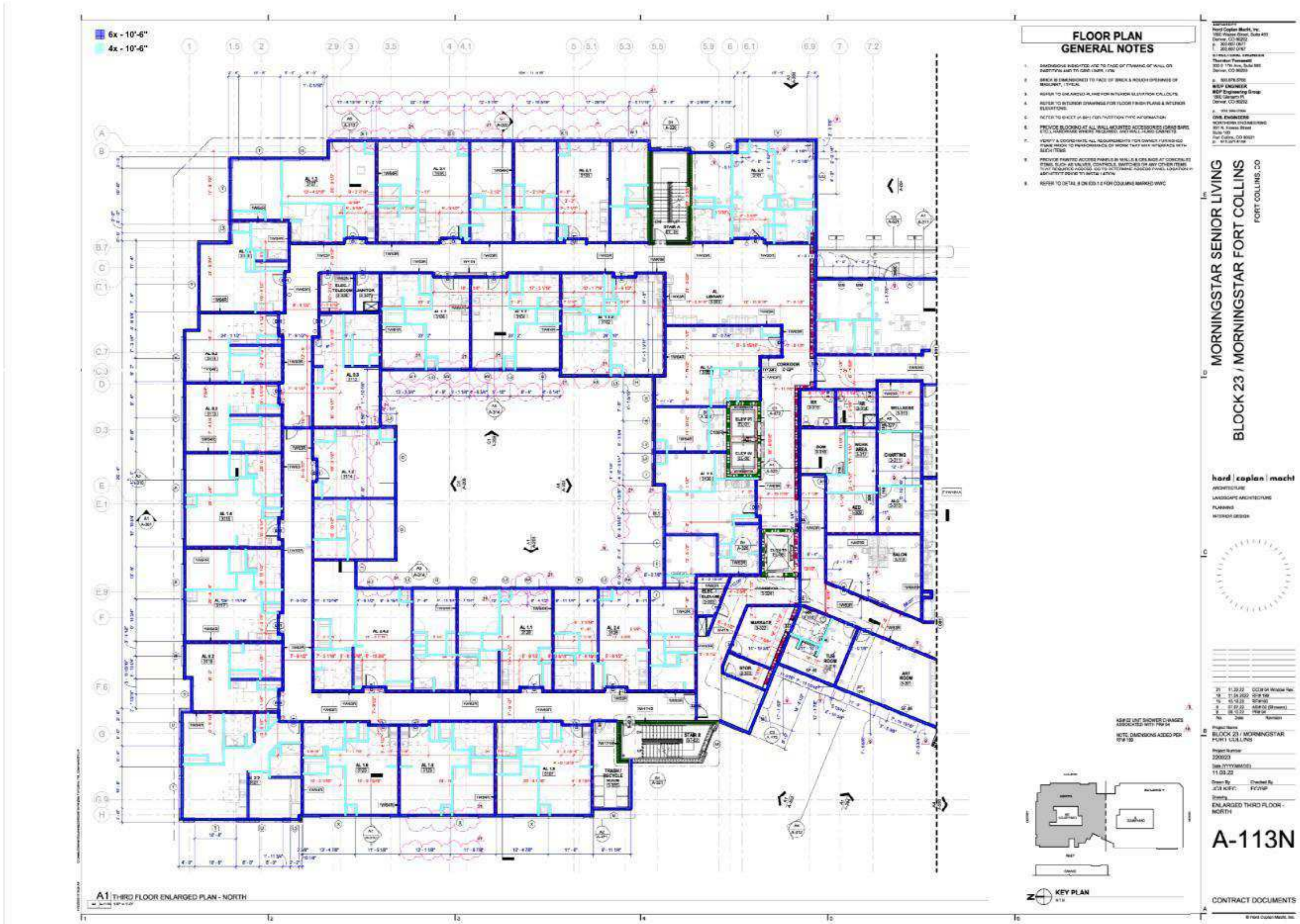
Site Built Walls – Level 3



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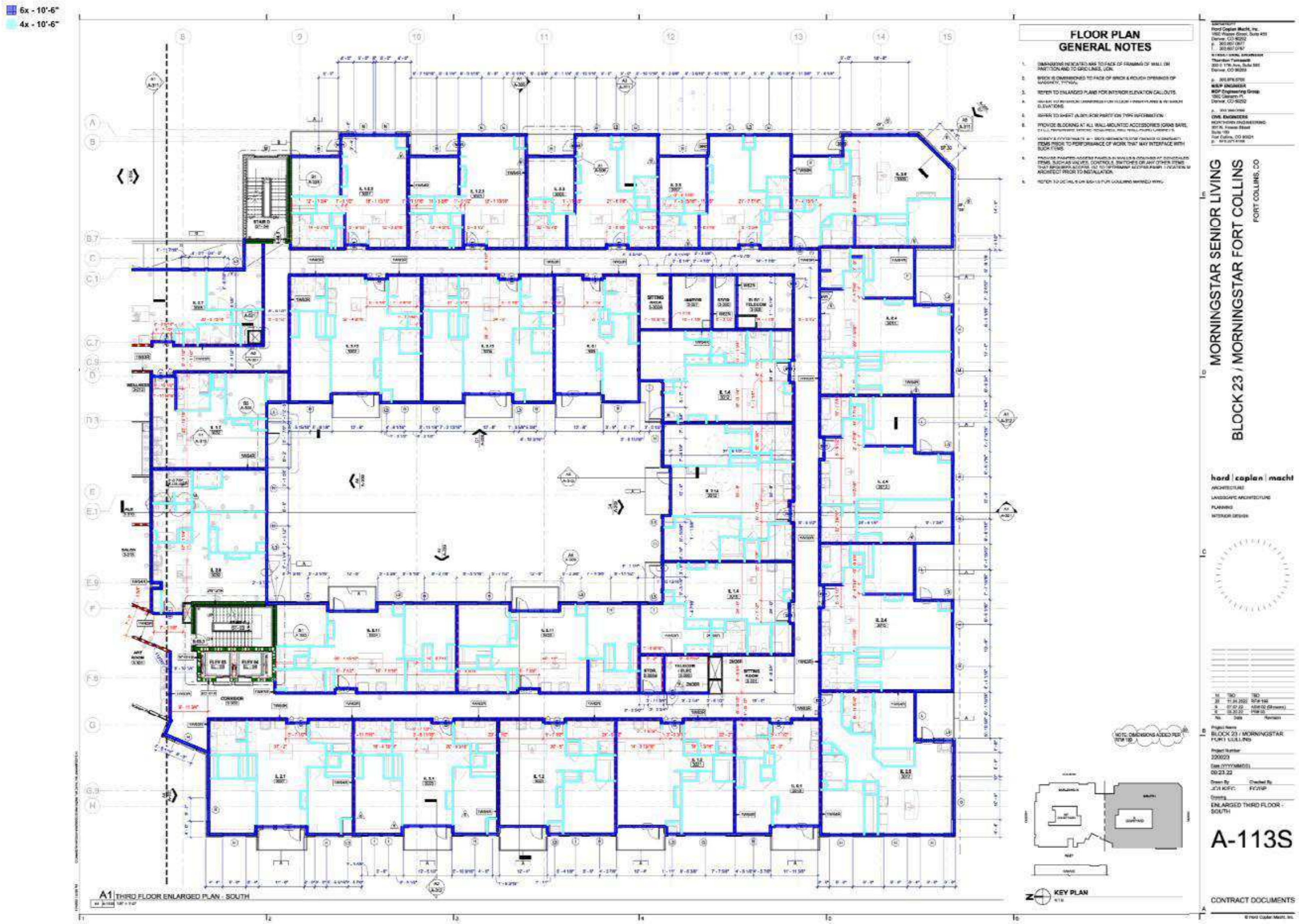

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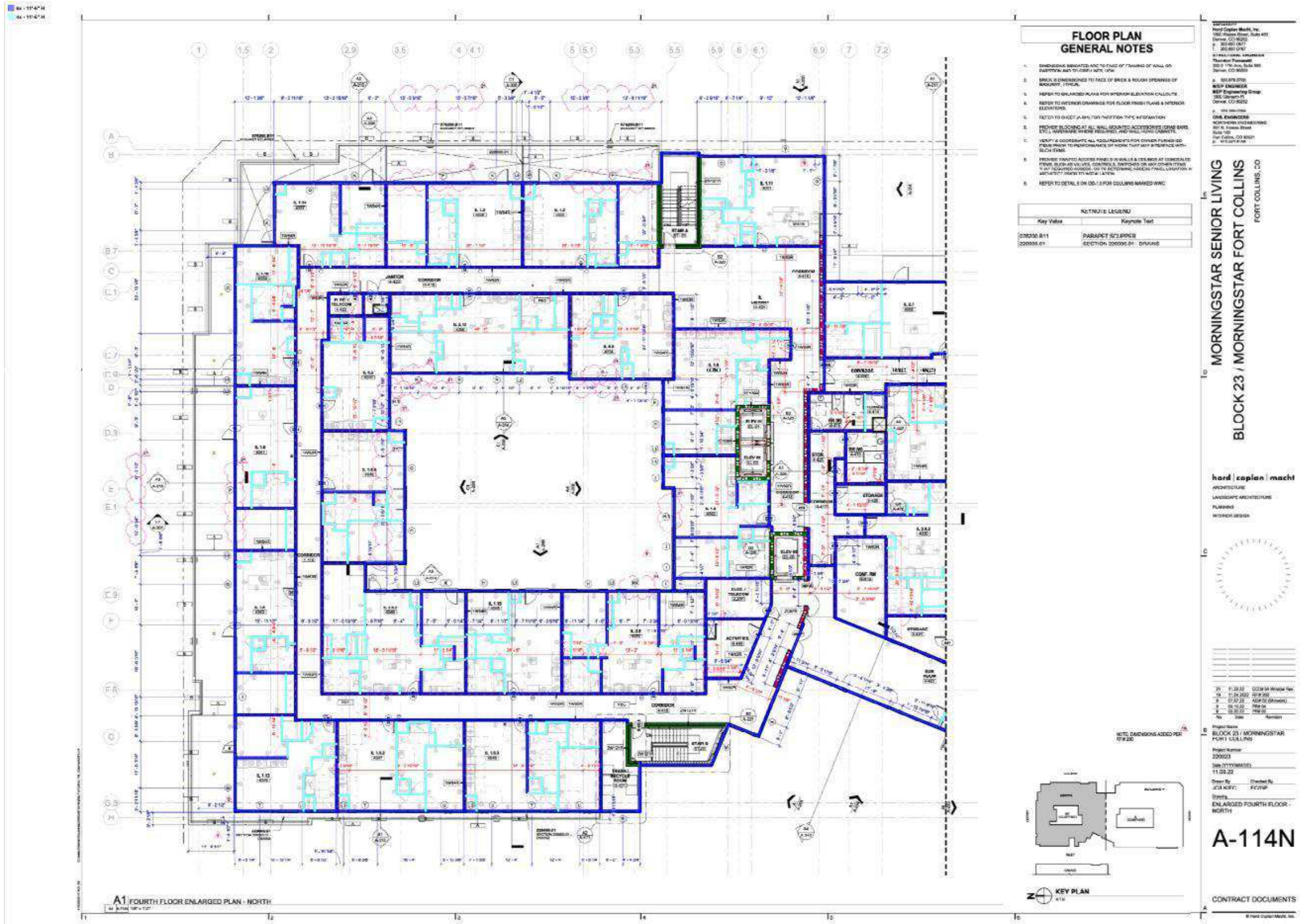
Site Built Walls – Level 4



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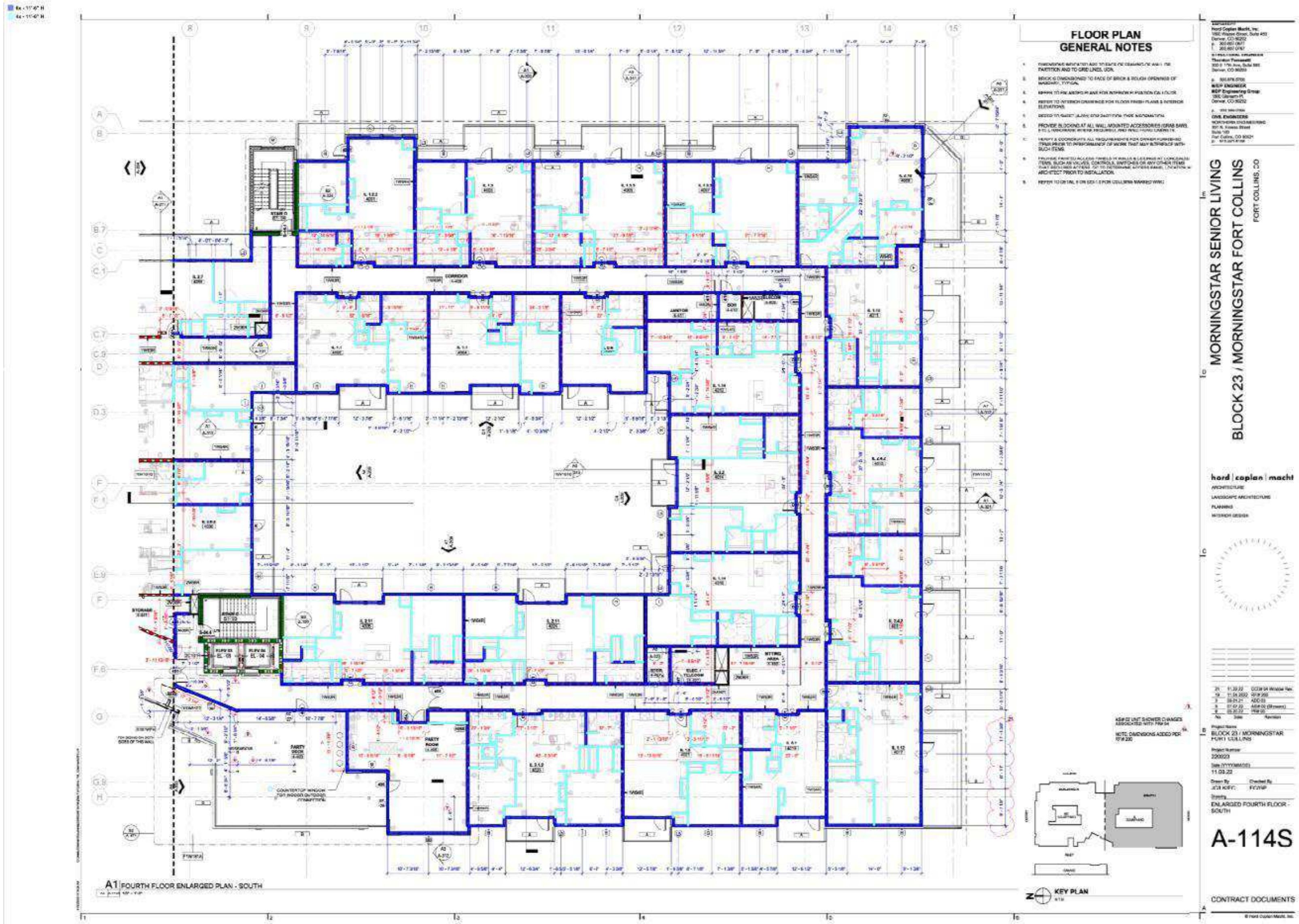

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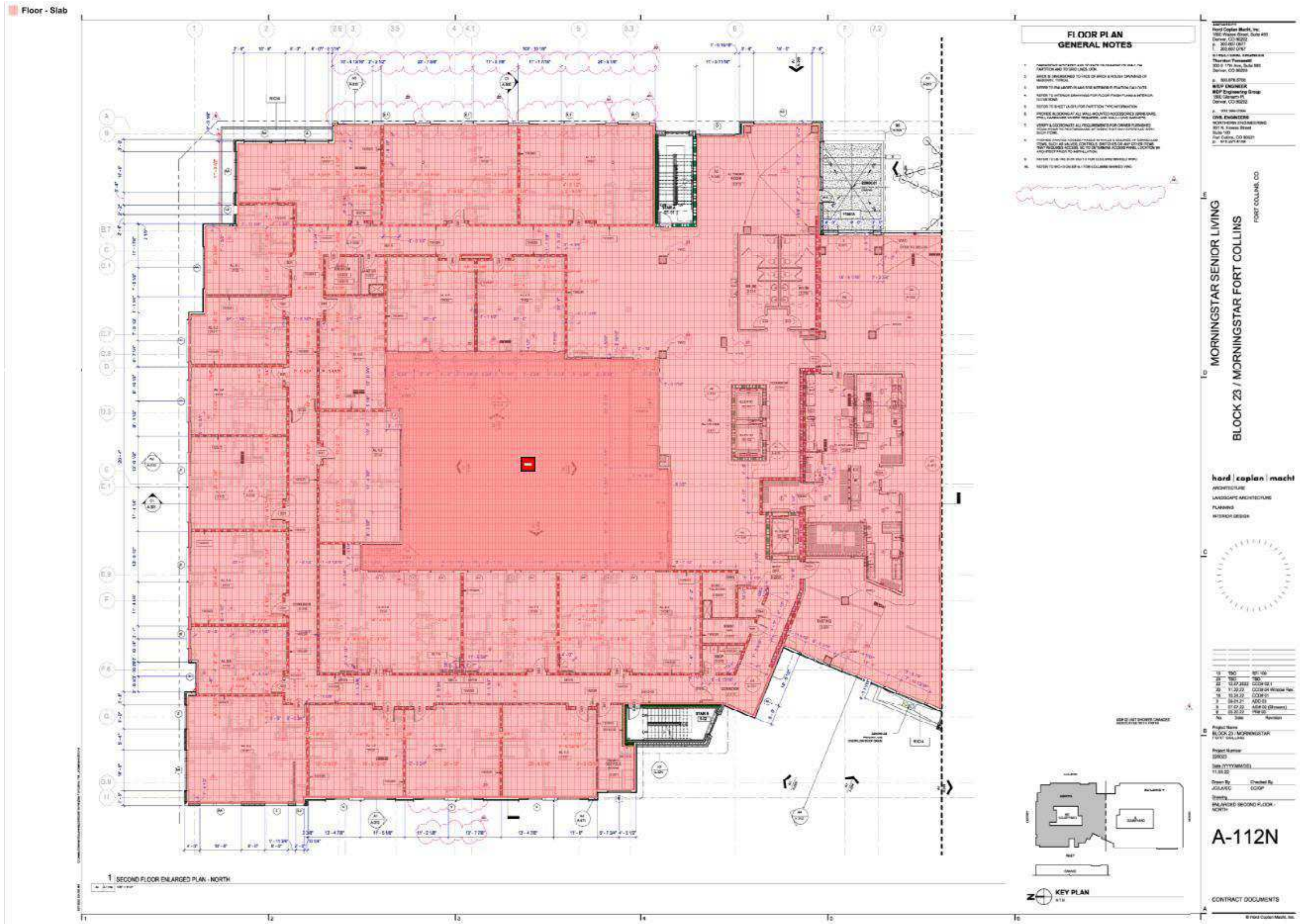
Site Built Floors – Level 2



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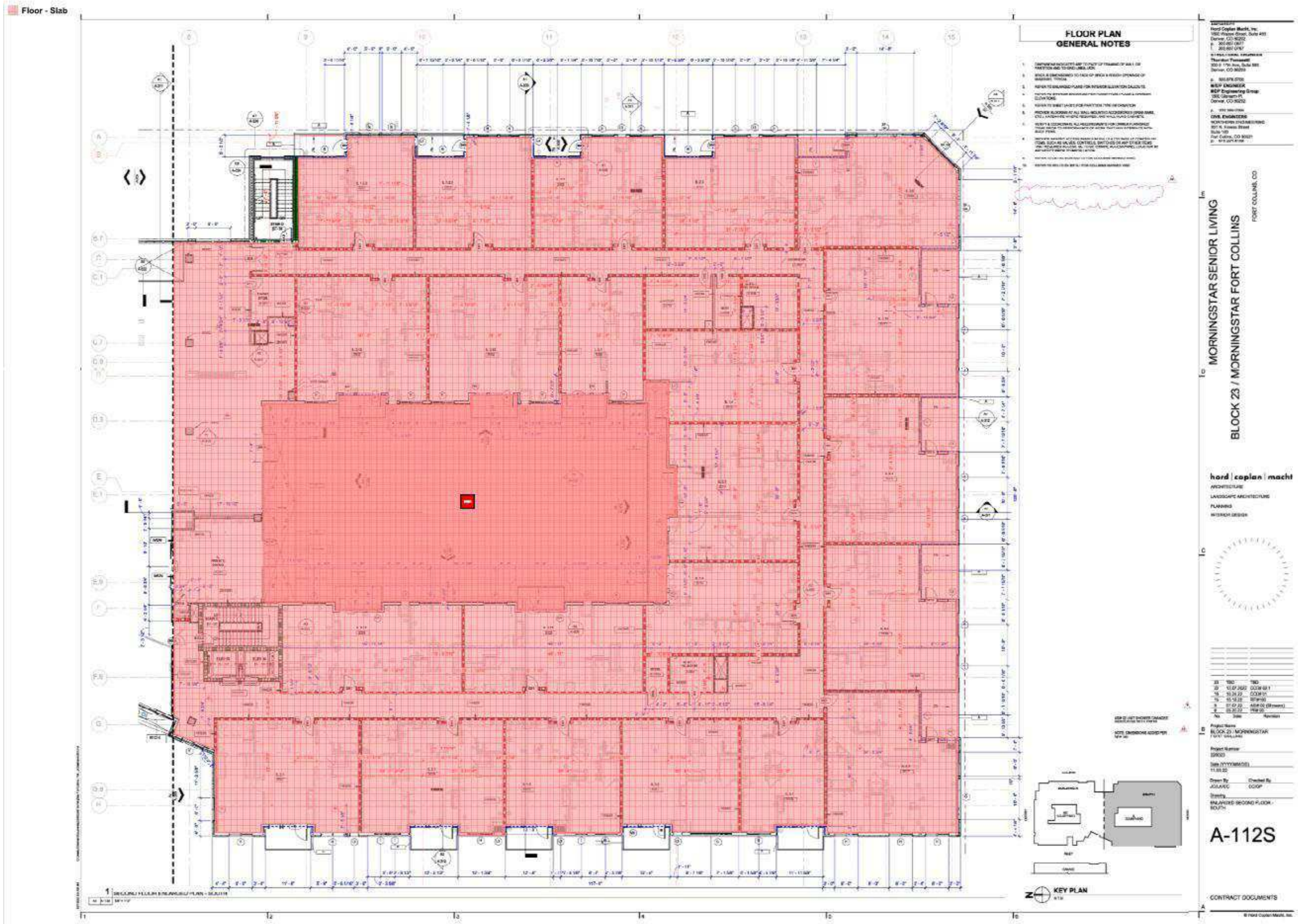

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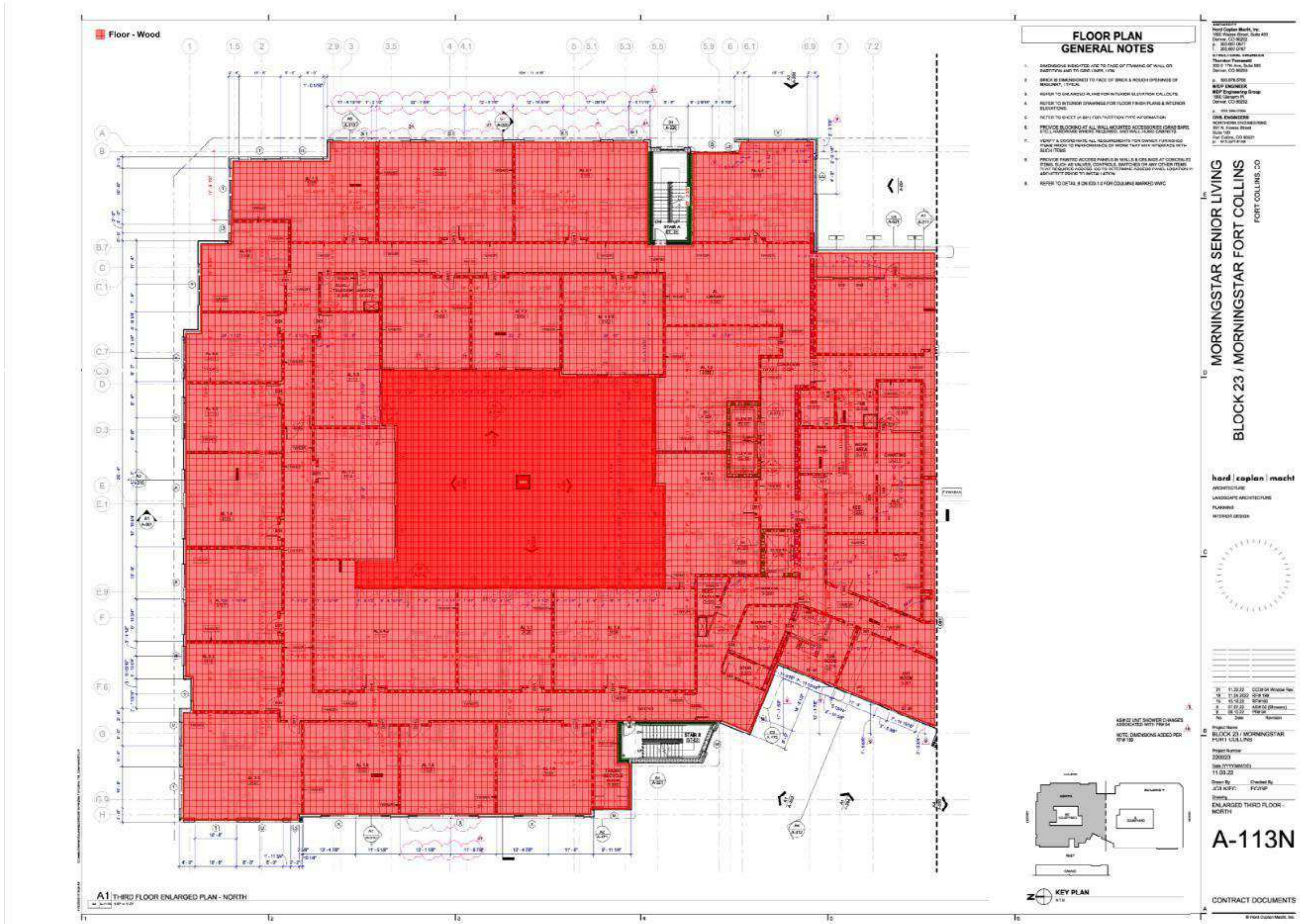
Site Built Floors – Level 3



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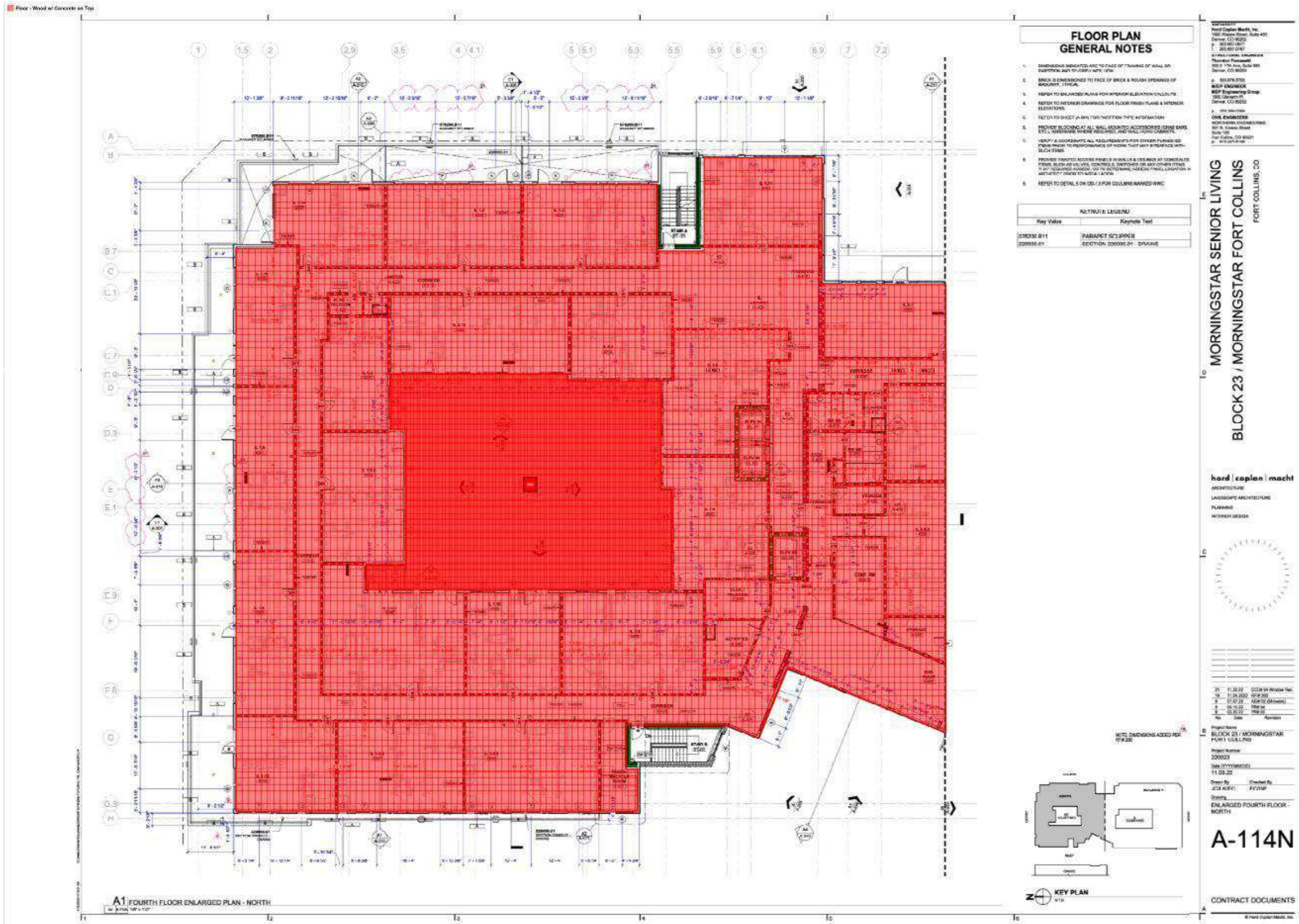
Morningstar_Architectural Plans.pdf (18) (26% of Scale); Takeoff in Active Area: All Areas; Morningstar_Site Built; Morningstar_Site Built; 10/7/2023 12:00 PM

Site Built Floors – Level 4



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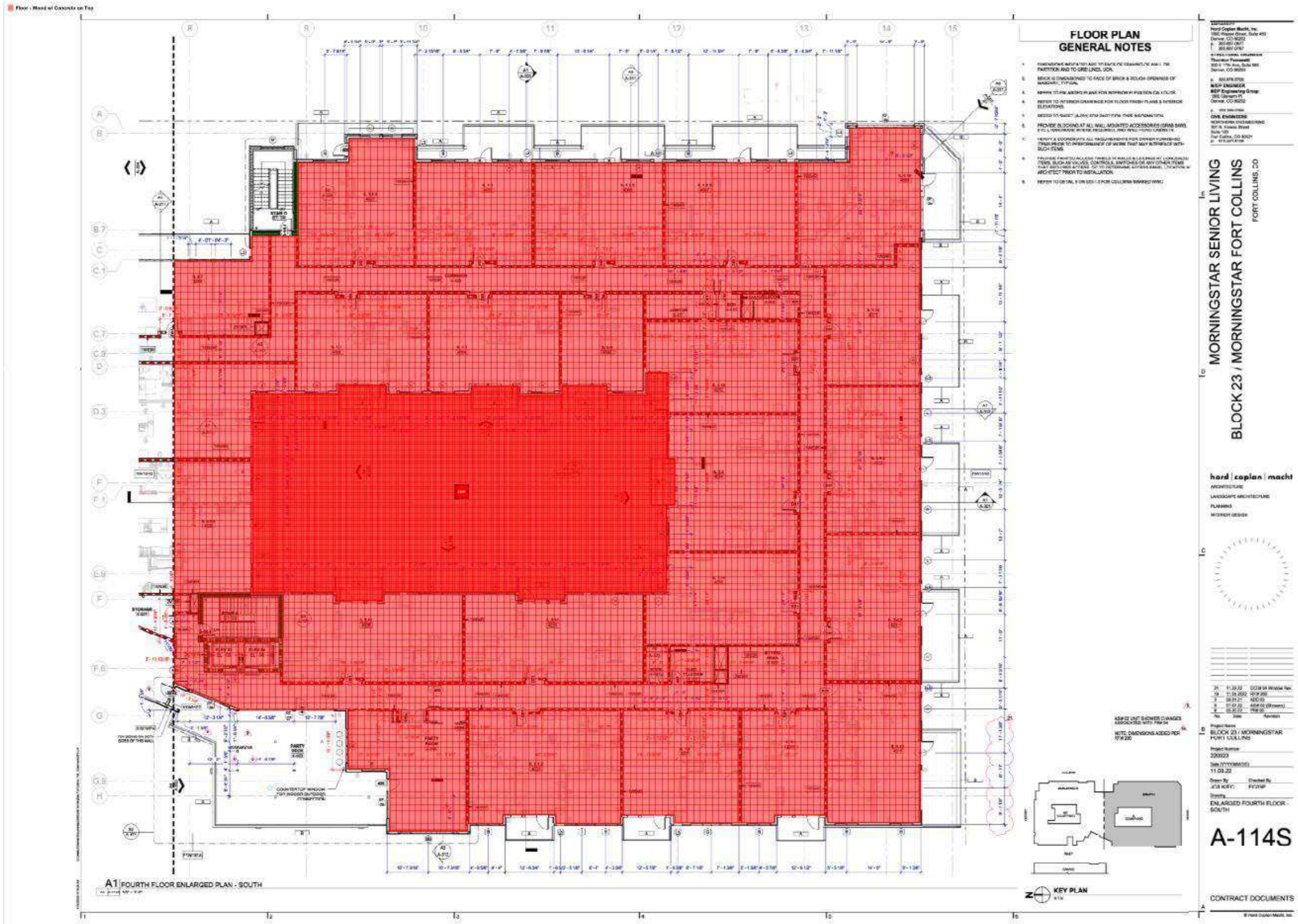

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Site Built OST Takeoff – All Levels

Takeoff Tab

Morningstar_Site Built

Bid No. 1

No.	Name	Height	Area	Quantity1	UOM1	Quantity2	UOM2	Quantity3	UOM3	Notes
2nd Floor										
2	4x - 11'-6" H	11' 6"	(unassigned)	4,191	LF	48,200	SF	14,058	CF	
1	6x - 11'-6" H	11' 6"	(unassigned)	5,192	LF	59,713	SF	27,368	CF	
3	Floor - Slab	0"	(unassigned)	54,677	SF	0		0		
3rd Floor										
7	4x - 10'-6"	10' 6"	(unassigned)	4,431	LF	46,521	SF	13,569	CF	
6	6x - 10'-6"	10' 6"	(unassigned)	6,066	LF	63,689	SF	29,191	CF	
5	Floor - Wood	0"	(unassigned)	54,344	SF	0		0		
4th Floor										
8	4x - 11'-6" H	11' 6"	(unassigned)	3,388	LF	38,965	SF	11,365	CF	
9	6x - 11'-6" H	11' 6"	(unassigned)	5,524	LF	63,529	SF	29,118	CF	
10	Floor - Wood w/ Concrete on Top	0"	(unassigned)	47,676	SF	0		0		