TOWARDS ASSESSING BUILDABILITY IN WOOD FRAMED, SUPERINSULATED WALL ASSEMBLIES

by

Nicholas P. Erb

HBOR, BA Lakehead University, 2003

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ABSTARCT

Towards Assessing Buildability in Wood Framed, Superinsulated Wall Assemblies

Masters of Building Science, 2014

Nicholas P. Erb

Building Science

Ryerson University

A superinsulated home has many attractive attributes including reducing CO_2, saving energy and smaller energy bills. The Passive House certification—which originated in Europe—proves that superinsulating is an effective way to reduce energy consumption. As the popularity of superinsulation grows in North America, the need to assess the buildability of these structures increases. This MRP identifies six metrics of buildability for wood framed, superinsulated walls and creates a tool which can be used to assess the buildability of these assemblies. The tool will assess a specific set of working drawings in their local context. The tool is simple to use, assuming that the user has an understanding of the basics of building science and an understanding of the capabilities of the local trades and the local availability of materials. The initial tool was tested by identifying the strengths and weaknesses of a series of case studies for most of the metrics. A revised tool is proposed which has been refined to address the shortcomings of the initial tool.

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DEDICATION

To my mother, Diana Erb, a woman who fought harder for my early education than any mother should have to. I have dedicated my life to learning and it is thanks to her that I have made it this far.

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List of Terms and Abbreviations

TJI	Trust Joist
PH	Passive House
PHI	Passive House Institute (Europe)
PHIUS	Passive House Institute US
SIP	Structural Insulated Panel
CEPHUSE	Cost Efficient Passive Houses as European Standards
MRP	Major Research Project
BIM	Building Information Modeling
O/C	On Center
DWS	Deep Wall System
FST	Fuzzy Set Theory
ISO	Polyisocyanurate
SBPO	Spun-Bonded Polyolefin
N/A	Not Applicable
‘	Feet
“	Inches
cu ft	Cubic Feet
sq ft	Square feet

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CHAPTER 1: INTRODUCTION

1.1 Introduction

The scientific community agrees overwhelmingly that climate change is caused by human activity (Oreskes, 2004). The results of climate change are expected to impact every living thing on this planet. Today, reducing greenhouse gas emissions is an important way to decrease the magnitude and rate of change (Warren, 2014). A reduction in emissions can come in many forms, and the shift associated with that reduction will affect the way humans live on this planet; however, without this shift, the effects of climate change will be more severe. Arguably, it is too late to stop climate change, and therefore humanity's best path forward is to mitigate the effects of climate change by doing all that can be done to impede the warming of the planet. A reduction in greenhouse gas emissions is directly related to a reduction in energy, as much of the secondary energy consumed today—such as oil and coal—produce CO_2.

Housing is a significant portion of secondary energy use. In Canada, the home accounts for 17% of the nation's secondary energy (National Resources Canada, 2014). As well, heating makes up a significant portion of the energy used in homes in cold climates. In Canada, space heating accounts for 63% of the average home's energy use (Natural Resources Canada, 2014). As the home is a significant portion of energy consumed on a national scale, and heating is the major proportion of energy consumed in homes in a cold climate, by dramatically reducing the heating requirements for homes, the production of greenhouse gasses will be reduced.

Another reason to reduce energy consumption in the home is related to cost. In Ontario, where natural gas is the most commonly used fuel for heating, Enbridge, Canada's largest natural gas distribution company, threatened to increase gas price 40% after a particularly cold winter (Pedwell, 2014). In terms of the resources that create some of our energy—such as natural gas and oil—their quantities are fixed. As their stocks diminish, their costs are sure to increase. By limiting the amount of energy a home requires for heating, a home owner is limiting their dependence on ever-increasing fuel prices.

An example of the relationship between the cost of energy and its consumption can be found when comparing usage between North America and Europe. Energy is more expensive in Europe, and in

Europe they use less energy. North Americans pay much less for their energy, and consume significantly more energy than their European counterparts (International Energy Agency, 2008).

One of the ways some European countries have moved towards reducing the energy required in their homes is through a certification called “Passivhaus.” The Passive House Institute (PHI) has very specific energy goals regarding heating and primary energy use. By achieving these energy goals, a Passivhaus can see savings related to heating and cooling of 90% over typical building stock and 75% over the average new build (Passive House Institute, 2012).

How does Passivhaus achieve such significant reductions? The efficiency of the equipment and appliances in these houses is a part of the reduction; however, the feature that plays one of the biggest roles in curbing energy consumption is the building envelope. To achieve the significant reduction in space conditioning, PHI requires a very tight envelope of 0.6 ACH at 50 Pa, and a superinsulated structure free from thermal bridges. Superinsulating the building’s envelope minimizes heat transfer to the exterior. Passivhaus sees amazing reductions in the energy required for heating and cooling by controlling air flow and heat transfer through walls. This MRP will focus on the creation of a tool for assessing the buildability—or ease of construction—of superinsulated wall assemblies.

1.2 Research Background

The Passive House Institute of the United States (PHIUS) has arrived, and homes built in North America are being certified. However, the North American climate and building techniques are dissimilar enough from Europe that the methods of construction which were successful for PHI projects in Europe must be adapted for PHIUS buildings. Therefore, North American designers and builders must vary from the European vernacular when designing assemblies for the North American context.

The reference material too must be revamped to reflect North American building techniques. One of the major PHI references in Europe is *Details for Passive Houses* (2009), a book of wall sections and specifications which is used by planners, architects and builders. PHIUS and Richman (2013) are working on a book entitled *Passive House Design Details* which seeks to create the PHI reference for North America.

To date, the only measure of buildability for superinsulated assemblies in North America is presented in *High-R Walls Case Study Analysis,* by Smegal and Straube (2012). In their article, Smegal and Straube create an “out-of-five” ranking system where “5” is the ideal in terms of buildability and “1” is undesirable. The rankings by Smegal and Straube are judged subjectively, based on the expertise of those working with these assemblies in industry on both the design and construction sides. The results are comparative, where one assembly is given a higher score than another and is therefore more buildable. The ranking of superinsulated assemblies in their article is too broad, however, and is only useful for a general sense of the buildability of a type of assembly.

1.3 Objectives

The objective of this MRP is to create a tool which will be used to judge the buildability of North American wood framed wall assemblies, in new construction. The audience for the tool would be building science professionals, or designers and contractors with a base knowledge of building science related to wall assemblies. The tool will be able to identify barriers to the ease of construction of a wall. There will be a specific focus in this MRP on superinsulated assemblies as these walls are generally thicker and more complex to construct. The tool will build on the work in *High-R Walls Case Study Analysis* (Straube & Smegal, 2012), being both subjective and comparative. However, the tool will go a step further by addressing specific assemblies in their local context and breaking down buildability into the metrics which affect the construction ease of these assemblies, so that the relative weakness or strength in an element of assembly is identified.

1.4 Problem Statement and Research Questions

The Passive House Institute US has certified over 1000 consultants and over 100 projects in North America (PHIUS, 2011). Passive House certification is one reason why superinsulated structures are being built in North America and there are many others including limiting energy consumption to reduce CO_2 emissions, increasing resiliency and decreasing energy bills. *There is no convenient way at this time to judge the buildability of a specific wall assembly in its local context.* This MPR will create a tool for assessing buildability in North American site built, wood framed assemblies. The tool created for this MRP will enable a clearer understanding of how different aspects of a superinsulated wood framed wall assembly affect that wall's buildability.

This project is criteria-driven and will seek to answer the following research questions:

1) What are the major metrics of wood framed wall assembly buildability?
2) How can those metrics be assessed?
3) Using four case studies presented in this MRP, can the buildability of these assemblies be evaluated by a method based on the above metrics?

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter will examine the work previously undertaken regarding buildability and its cognate term, "constructability," in the context of defining the terms associated with the buildability assessment tool developed in this MRP. The chapter will then discuss the following: Passive House in a North American context, three of the key articles on North American superinsulated wall assembly buildability, and finally, the methods of judging buildability.

2.2 Interpretation of Buildability and Constructability

Constructability and buildability have been defined in many different ways by many different authors. Pocock et al (2007) defines constructability as a "project characteristic that reflects the ease with which a project can be built and the quality of its construction documents" (Pocock, Gambatese, & Dunston, 2007). Pocock is suggesting that context is a vital part of the judgement of constructability. He contends that what should be assessed are the characteristics of a specific project as well as its working drawings and their quality or clarity. Holroyd (2003) stresses the importance of knowledge of the trades to the constructability process. According to Holroyd (2003), tradespeople need to understand their role, designers have to listen to the trades, and engineers have to work together with both parties. Boyce (1991) compiled a list of the ten factors which, if followed, will lead to better constructability, based on the KISS Principal (Keep It Simple Stupid). He states, "The goal of designing for constructability is to make a project easier to engineer, to procure, and to construct while maintaining quality, accessibility, and cost effectiveness for construction, production, and maintenance" (Boyce, 1991).

Common themes appear in definitions of constructability and buildability including ease of construction, design, quality and efficiency. As part of his doctoral thesis, Wong (2007) looked at the interpretation of both constructability and buildability—20 definitions in all—and found this distinction between the two:

> *In general, it can be said that "buildability" is concerned with the design facilitating ease of construction, whilst "constructability" deals with the whole process of project development to enhance construction efficiency* (Wong, 2007).

This suggests that "buildability" deals with the very practical, hands-on aspects of construction while "constructability" deals with a larger picture that might include or be similar to an integrated design process. Thus, constructability is more than simply the *ease* with which the building goes together.

Wong's definition of "buildability" is: "The extent to which a building design facilitates efficient use of construction resources and enhances the ease and safety of the construction site whilst the client's requirements are met" (Wong, 2007).

Straube has a more simple definition of buildability: "the perceived complexity or deviation from standard practice of different construction techniques" (Straube & Smegal, 2012). As this research will show, "deviation from standard practice" is the seminal factor identified as affecting buildability, as many experts agree.

Passive House assemblies would generally be considered less buildable in North America. This is because the dramatic energy savings associated with PH require a superinsulated wall, which are thicker than standard practice North American wall assemblies and therefore take more time and materials to build. The appeal of a PH lies not in their buildability or even necessarily in their constructability, but rather in their potential for significant energy savings.

2.3 Passive House in North America

Passive House came to North America largely from Germany—a country with a temperate climate. As the North American context often demands an increase in heating, the difficulty of achieving PH certification also increases, because PH requires significant energy reduction per m^2. "In Europe, achieving the [Passive House] standard is a pretty steep mountain to climb, but we build in Bemidji Minnesota – a much colder climate," says Stephan Tanner, the architect of the BioHaus (Anonymous, 2006). Apart from climate, building techniques and materials also differ in North America. Though stick framing is common in Passivhaus homes in cooler European climates such as Sweden (Boqvist, 2010), the construction of a standard Swedish home is much closer to PH than most standard homes in North America. The differences between Swedish homes and North American homes are significant, and a new approach to stick frame construction for North America is required to build PH structures there.

In their article on the Cost Effective Passive Houses as Europeans Standards (CEPHUES), Schniders and Hermeik (2006) voice a frequently-heard idea regarding PH: "The improved construction quality of the building envelope and the highly efficient ventilation systems in Passive Houses require extra investment. If the approach is pursued rigorously, this is counterbalanced by the avoided investment cost for a conventional heating system." This idea is illustrated in the graph below (see Figure 1). When the capitalized cost is high, the required energy for heating is low. As the investment shrinks, the heating requirements grow. After 15 kWh/m^2, there is a steep shift upwards in the capitalized cost caused by the addition of a heating source. In much of Canada, where the climate can have a larger temperature range than Europe, the heat gains from inhabitants, lighting, appliances and passive solar are not enough to make a central heating source redundant at 15 kWh/m2.

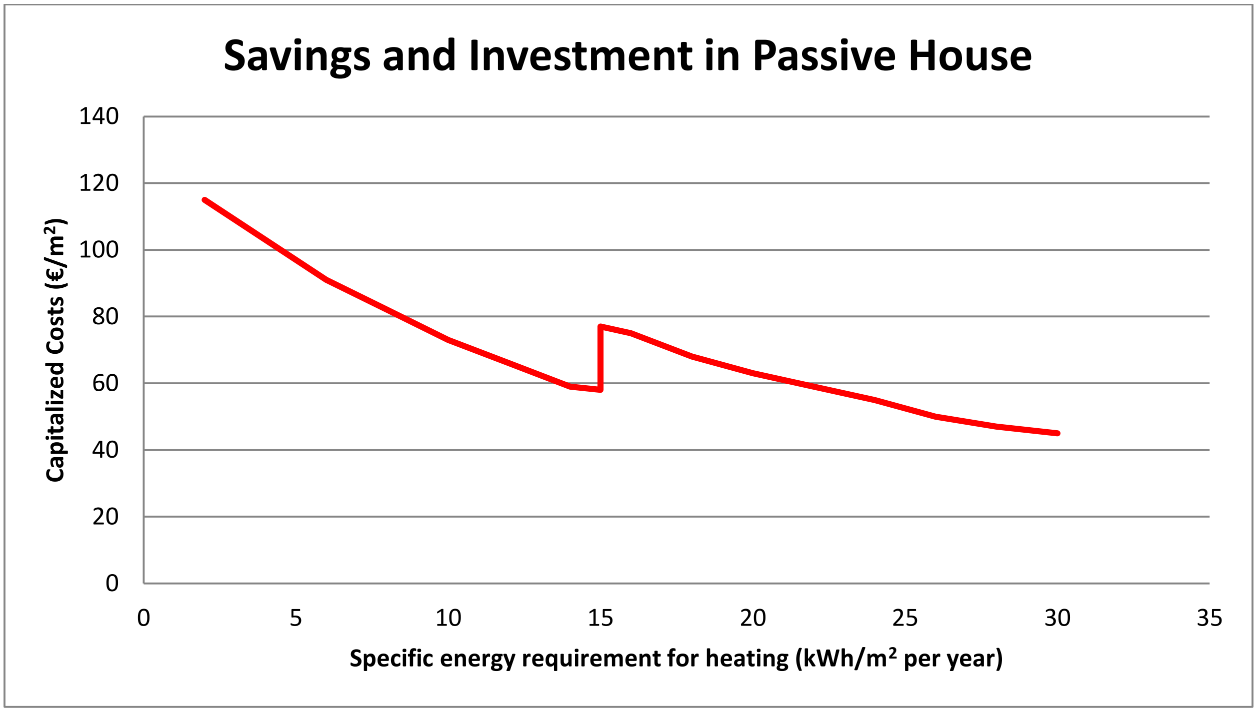


Figure 1: Passivhaus, capital cost against energy require for heating (Schniders & Hermeik, 2006).

The above graph shows that, in Europe, there is potential to build a PH at a similar cost to a conventional dwelling by taking the money saved on heating equipment and shifting it towards insulation. This is not true of the many places in North America that have a cooler climate than their European counterparts. A PH in North America will likely not have a similar cost to a conventional home because of the extreme levels of insulation and because of the addition of a conventional heating system. Therefore, a North American PH runs into more difficulties than many of their European counterparts, regarding the high initial investment cost and longer-term life cycle savings. The initial investment in a home with an advanced envelope is great, but there is always a pay-back period in which energy savings amount to more than that initial investment. For a PH in many climates in North America, this payback period is unreasonably long, and significantly longer than in Europe (Audenaert, De Cleyn, & Vakerckhove, 2008). Therefore, for a PH to make sense financially in North America, the cost of energy would have to increase dramatically. This is not to say that energy prices will not increase to a point where the North American PH has a reasonable payback, or that there are not many other reasons to choose a PH (for example, less reliance and pressure on local amenities). This is simply stating that, with the cost of energy at present, PH in North America has a very long payback period—one that most home owners would likely consider unreasonable.

To reach the energy savings for heating associated with PH, walls must show significant thermal resistance; these kinds of walls, however, are more vulnerable to moisture collection (Straube & Smegal, 2012). In a conventional North American wall assembly, potential moisture-related problems are addressed through a vapour retarder on the interior of the insulation. The energy transmission through a traditional assembly increases the drying potential in these walls to the exterior (Straube & Smegal, 2012). As heat travels from the interior space to the exterior, the conventional wall—which is less thermally resistant than a PH wall— is maintained at a warm temperature, preventing condensation. Superinsulated walls increase thermal resistance, which fulfills one of PH's objectives, but the loss of heat transfer in the wall reduces the wall's drying potential and can lead to moisture building up inside the cavity (Holladay, How Risky is Cold OSB Wall Sheathing?, 2010). In a superinsulated assembly with sheathing outboard of the insulation, that sheathing is no longer warmed by the energy transfer from the interior. The result is cold exterior sheathing, which causes moist air in the cavity to condense. A wall that collects moisture is a serious problem affecting the durability of that wall, and creating the potential for both rot and mold.

In terms of buildability, PH doesn't require a big shift in what products are used; rather, it requires a shift in how the products that are already available in North America are used. "Passive houses do not require any components not found in traditional construction but the difference and difficulty is rather that the components must be assembled in accordance to an energy efficient design" (Boqvist, 2010) with strict attention to details. The familiarity with the products will help PH in terms of buildability in North America: that is, the similarity of the products to standard practice will ease the transition to PH. If builders use material that they are already familiar with, this is one less obstacle in the way of acceptance and success. As well, the technique used most often in North America for building a home—stick framing—is similar to the method used in PHs in colder regions of Europe. "In cold regions (in Europe) the wooden lightweight construction dominates" (Boqvist, 2010). Light frame wood construction is done differently in Europe and North America. Whereas in North America a single cavity created by a 2x4" or 2x6" stud, filled with insulation, with a vapour retarder on the interior and sheathing, followed by a layer of spun-bonded polyolefin (SBPO) on the exterior, is common practice in many assemblies, Swedish walls have a deeper stud cavity of closer to 7 ¾" with up to 2" of mineral wool on the exterior and an interior chase cavity inboard of the air barrier—which protects the air barrier from penetrations—filled with another 2" of insulation (La Vardera, 2010). While many North American builders would be a long way from following these Swedish techniques today, builders can still benefit from the lessons that the Europeans have learned via the successful examples and techniques that incorporate materials that the North American builders are comfortable with.

The quality of details is more important in a PH than it is in standard practice (Boqvist, 2010). Whether it be where the slab meets the wall assembly, where the wall meets the roof or where there are penetrations, every detail must be carefully examined to ensure the continuity of the barriers, insulation and retarders. For ease of buildability, details must be clear and explicit; they must reflect the building practices of the local area and the crew, and they must be optimized towards success, which could involve including redundant barriers and effectively sequencing the order of construction (Bates, 2012).

2.4 Buildability in Superinsulated Wood Framed Assemblies: Key Studies

The current interest in superinsulated wood framed assemblies is reflected in the number of studies that describe these types of wall; this section therefore will move through three important articles as they relate to this MRP.

"High-R Walls Case Study Analysis" (Smegal, Straube, 2012)

Part of the academic work related to the specific topic of buildability in superinsulated wood framed wall assemblies in North America was conducted by Straube and Smegal (2012). In the analysis, "buildability" is described as "the perceived complexity or deviation from standard practice of different construction techniques" (Straube & Smegal, 2012). What Straube and Smegal call "standard practice" is the most basic wall assembly: 2x4 or 2x6 at 16" on-centre, satisfying local code requirements. Standard practice is thus assumed to be perfectly buildable. They go on to explain that to achieve the greatest benefit, at the production level, the detail drawings must be clear (Straube & Smegal, 2012). This mean that if an assembly is either more complex or deviates from standard practice, the details should still be clear enough and related to standard practice so that the assembly is buildable and therefore has a point of reference from the trades to eases the construction.

Straube provides a ranking system for walls based on his opinion and the opinions of five industry professionals with experience in building superinsulated wall assemblies. As would be expected from Straube's definition of buildability, standard wall construction is given 5 out of 5. Standard practice is the wall against which all other wall assemblies are judged. “(A)ll of the trades and construction industry are very familiar with building [a standard construction practice] wall system” (Straube & Smegal, 2012). This practice is the norm and therefore can be built to the standards required by any professional in the industry.

For the first type of superinsulated wall used in this research, which features exterior insulation, Straube says that the buildability out of 5 is decreased to 4. “Changes are very minimal for insulation sheathing thicknesses of 1.5” (38mm) and less, but for insulating sheathing thicknesses of 2” (51mm) and greater, special details are required for cladding attachment and window and door installation” (Straube & Smegal, 2012). Ultimately, to a particular thickness, an assembly with exterior insulation can be treated in a similar manner to the standard practice and therefore is highly constructable. However, as that insulation becomes thicker and approaches levels which would be considered superinsulating, a number of difficulties arise, including how the insulation is attached to the structure and how the insulation is integrated into the structure’s openings. These factors decrease the buildability and increase the time required for the additional application.

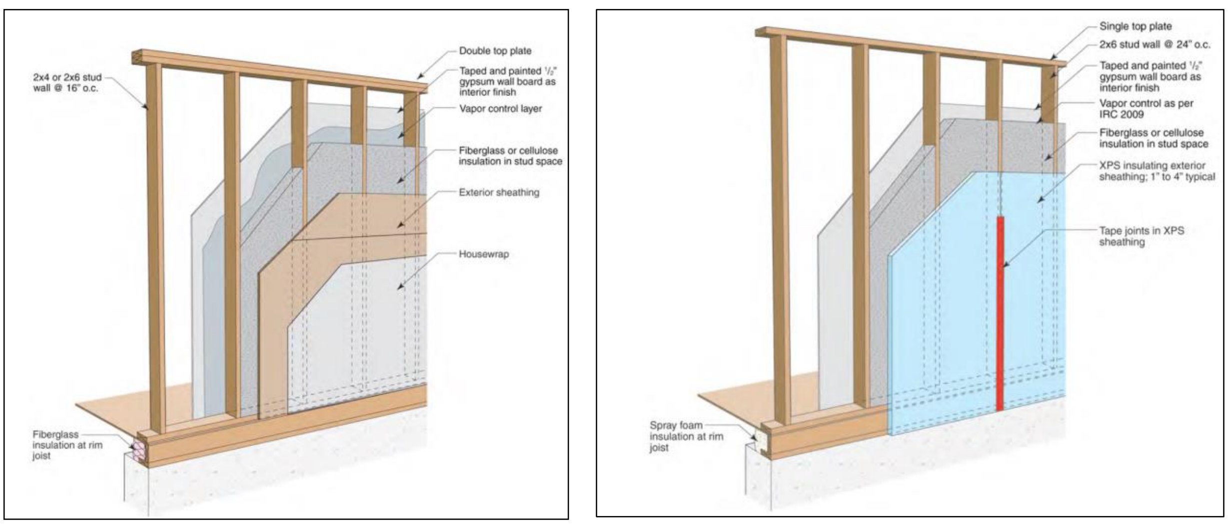


Figure 2: Standard construction practice (left), and advanced framing with insulated sheathing (right) (Straube & Smegal, 2012).

For double stud wall construction, Straube drops the buildability score to 3 out of 5. Though the wall is not particularly complicated in terms of the framing, there is twice the number of walls, and so the connections between the two walls become complicated. Straube and Smegal use the example of window bucks (plywood boxes) as one of the additional steps related to double stud wall construction (Straube & Smegal, 2012). If the wall juts in or there is an exposed floor, the construction of a double stud wall becomes even more complex. On the Building Science Corporation's website, Straube go into more detail than he does in his article regarding the buildability of this assembly:

> *If polyethylene is used as the air barrier, it is critical to seal it perfectly to avoid wintertime air leakage condensation against the sheathing. This construction generally does not address the thermal losses or air leakage at the rim joist. Because the second framed wall is constructed on the interior of the structural wall, the interior floor space is decreased. This wall is quite susceptible to construction deficiencies in the air and vapor barrier* (Building Science Corporation, 2009).

The ease with which a double stud wall can be built depends on the quality of not only the design but also the construction. Workmanship is of vital importance in this assembly with regard to the barriers. Buildability depends, in this case, on the sequence in which the barriers and retarders are applied.

If the air barrier is applied correctly to the exterior of the rim joist before the wall is built, and if the air barrier system is then integrated properly, chances are higher that the assembly will be successful. If on the other hand the sequencing is thrown off and the integration of the air barrier is treated as an afterthought, we may see some of the problems that Straube suggested (Building Science Corporation, 2009).

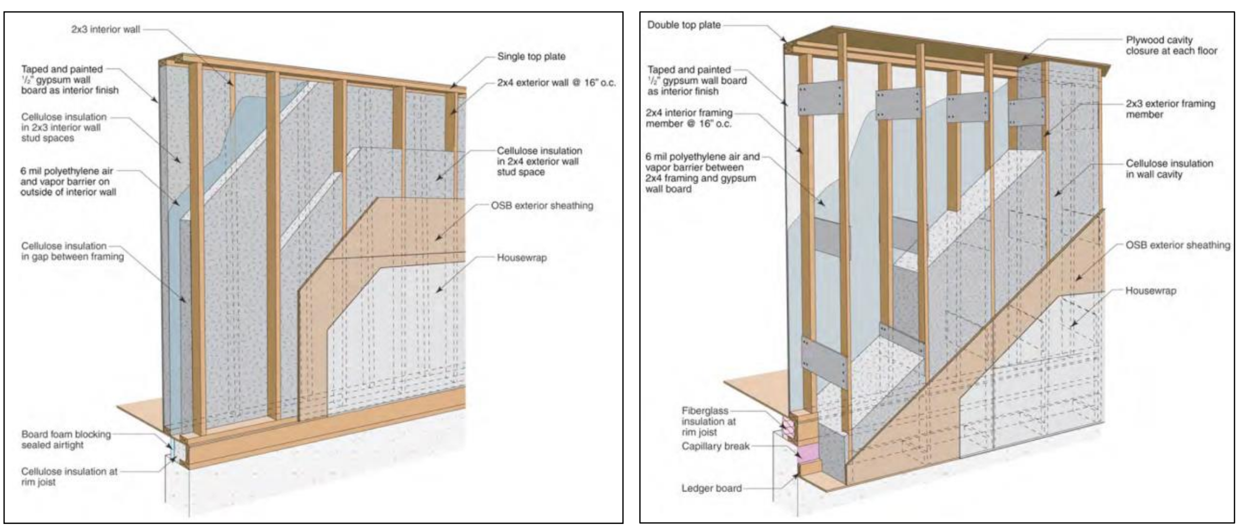


Figure 3: Double stud wall (left), and a Truss wall (right) (Straube & Smegal, 2012).

Straube gives a truss wall a 2 out of 5 for buildability. A truss wall varies greatly from standard practice; the application of gussets are time consuming because they require precision (Building Science Corperation, 2009). This assembly is also highly susceptible to moisture problems related to air leakage. Straube therefore suggests a combination of the airtight drywall approach along with a polyethylene vapour retarder (Straube & Smegal, 2012).

Though "High-R Walls Case Study Analysis" does not explicitly indicate the metrics which were used in judging buildability in these assemblies, it does suggest that the important factors seemed to be time, complexity, training, workmanship and connections. Ultimately, the assemblies are judged against each other and what is created is a general statement of that method; Straube doesn't even account for the variables that different local contexts can introduce. When asked specifically about the metrics used in this paper, Jonathan Smegal stated that they did not use any specific metrics and that from their panel of 5 experts a "feeling" regarding the buildability of each assembly was determined (Smegal, 2014).

"Evaluating R-40 Above Grade Walls for a Production Build Zero Energy House" (Broniek, Brozyna, & Stecher, 2010)

This article examines wood framed R-40 walls in Portland, Oregon. Broniek et al. built a 1.5 story mock-up in order to gain a better understanding of buildability for different framing systems. The relevance to this MRP was in terms of exterior insulation. Exterior insulation is generally seen as a positive attribute in an assembly, because it ensures that any water vapour that is travelling through the insulation cavity is less likely to condense on the exterior sheathing, as the sheathing's temperature is warmer than it would be if there were no exterior insulation.

However, the installation of exterior insulation can become complicated as the thickness of the insulation is increased.

> *The main disadvantage to using insulating sheathing that is greater than 25 mm (1") thick is that 19mm (¾") thick, vertically-installed, wood-based wall strapping is required for the installation of siding (either vinyl or fiber cement siding), which is the most prevalent façade finish in single family housing. The attachment of strapping adds another layer of work that builders could find onerous* (Broniek, Brozyna, & Stecher, 2010).

Whether or not the workers find the work "onerous," it deviates from standard practice by adding detailing, materials, time and possibly equipment in the form of scaffolding to the build.

The article also went on to identify a few of the factors affecting buildability, including the detail drawings, the trades, and what Broniek calls the "functionality":

> *For a wall system to score well for functionality, it must provide the same level (or better) of performance/utility as the wall it is replacing without additional resources* (Broniek, Brozyna, & Stecher, 2010).

Broniek also names weight as a factor, noting that, as the components' weight increases, larger vehicles are required to move the materials. As well, as the weight and size of components, increase they are increasingly difficult to handle on site because heavy materials often require scaffolding and the use of a crane. All of the factors, Broniek notes, decrease the ease of construction of superinsulated assemblies.

"Practical Residential Wall Systems: R-30 and Beyond" (Aldrich, Arena, & Zoeller, 2010)

Time, which is a significant factor in the sequencing and cost of a project, is highlighted in Aldrich et al. (2010). Double stud walls are seen as taking an extra "4-5 person-days for every 100 linear feet of exterior wall" (Aldrich, Arena, & Zoeller, 2010). This estimate includes the construction of the interior wall and window boxes, which are not required in standard practice.

Exterior insulation also sees an increase in time. The majority of the insulation installation is straight forward, but the installation for windows and door finishes will increase the time requirements for the project. It is expected that the increase in labour would be close to 30 hours on an 800 sq ft section of wall (Aldrich, Arena, & Zoeller, 2010).

2.5 Judging Buildability

There are many ways to judge buildability. Malek (2011) identifies three common methods for judging constructability and buildability. The methods include "regression," which involves mathematical equations derived for the values of aspects of constructability; "simulation," using programs such as BIM to ensure a project flows smoothly (though this is more closely related to a constructability review); and finally "Fuzzy Set Theory," which addresses the 'human factor' which Malek argues the other two methods leave out. "FST provides us not only with a powerful representation of uncertainties, but also with a meaningful representation of vague concepts better expressed in natural language" (Malek, 2011). The methods identified by Malek for judging constructability, which are intended for large scale construction projects, are inappropriate for smaller scale PH projects. PH projects are generally one-off single family dwellings. The benefits of assessing buildability rather than constructability are obvious.

Because these superinsulated assemblies generally deviate from standard practice, assessing the ease with which they can be built compared to standard practice is valuable. Much of the regression or simulation carried out in Malek's examples has little to do with buildability. A constructability review is another method often used in industry. This method was ruled out because it included every aspect of a project; however, this MRP is focused specifically on walls.

To determine the profitability of the Gemini NTED Design, Schlitt (2013) used the 5 Force model developed by Michael Porter of the Harvard Business School. This model allows the user an understanding of the competitiveness of a market, deeming the marked either "attractive" or "unattractive." Porter went beyond the rivalry among competing sellers and identified four other major factors affecting industry profitability (Thompson, Peteraf, Bambe, & Stickland III, 2012). For each of the five forces, a series of questions were created to identify the attractiveness of that specific force. As an example, the first question for "Threat of New Entry" into a market is: "What's the threat of new businesses starting in this sector?" (Hanlon, 2013).

The steps for using Porter's 5 Force Analysis are as follows:

> *Step 1: For each of the five forces, identify the different parties involved, along with the specific factors that bring about competitive pressure.*
>
> *Step 2: Evaluate how strong the pressures stemming from each of the five forces are (strong, moderate to normal, or weak).*
>
> *Step 3: Determine whether the strength of the five competitive forces, overall, is conducive to earning attractive profits in the industry.* (Thompson, Peteraf, Bambe, & Stickland III, 2012)

Porter's model is flexible enough to deal with multiple metrics, with varying factors in each. As well, it is simple enough to manipulate that it is a good fit for the scale of this MRP.

2.6 Literature Review Conclusion

A wall built according to standard practices is the most buildable wall because standard practice is "easy" in the sense that it is well-understood by all involved; this project aims to clarify how superinsulated wall assemblies can be assessed to determine how much they deviate from standard practice. A construction manager or site superintendent would appreciate a highly buildable project, largely because it will conform to standard practice. To use a woodworking analogy, a butt-joint, nailed together, is substantially more buildable than hand-cut dovetails.

Some of the confusion between "buildability" and "constructability" appears to relate to the differences between North American and European practice. In North America, the terms are used relatively interchangeably; in Europe, the distinction between the two is clearer (Wong, 2007). For the purposes of this project, "buildability"—the ease of assembling a structure—can be determined by looking at the design documents; that Pocock (2007) calls this "constructability" is indicative of the North American interchangeability of the terms. Constructability, on the other hand, has more to do with efficiency than ease. The owner of a building, who is concerned with not only the building process but also the life of the structure, appreciates a highly constructable project, which finishes on time, costs less, and is safer on site. It is more efficient to assemble a highly constructable project in terms of time, financial and human cost. A structurally insulated panel (SIP) home may be less *buildable* than a wood frame code assembly, because the SIP deviates from standard practice; however, with the appropriate resources and training, a SIP structure can go together dramatically more quickly and thus may be more *constructable*.

Constructability reviews have shown the power of constructability: it enables time savings, higher quality results, a safer work site, and other positive factors (Wissam Hijazi, 2009). However, there is a gap in the research: "The analysis of previous assessment methods revealed a lack of a clear and an accurate way to measure constructability" (Wissam Hijazi, 2009). This gap is where this MRP will fit.

For this research, the definition of "buildability" will be as follows:

> *Buildability is the ease with which a project can be built as related to the working drawings, the workmanship required, the experience of the trades and the complexity of the building shape.*

Achieving PH in North America requires significantly more precision, and thus more work, than standard practice; by being able to accurately assess buildability, the user will be able to identify impediments to their success, and thus avoid adding even more work to an already challenging project.

PH's European origins mean that the certification reflects a more temperate climate than much of North America. One fundamental feature of PH constructions is that they must not use more than 15kWh/m^2 for heating; this standard is much harder to meet in North America than it is in Europe, because the cooler North American climate means that homes built to PHI standards of insulation would never been able to achieve comfort at $15kWh/m^2$. The cooler climate means that PHIUS constructions must not only be superinsulated further than PHI standards: North American builds also require a conventional heating system. The greater investment in the envelope because of the climate and the added cost of the heating system makes for a very long payback period on a North American PH when compared to a European counterpart.

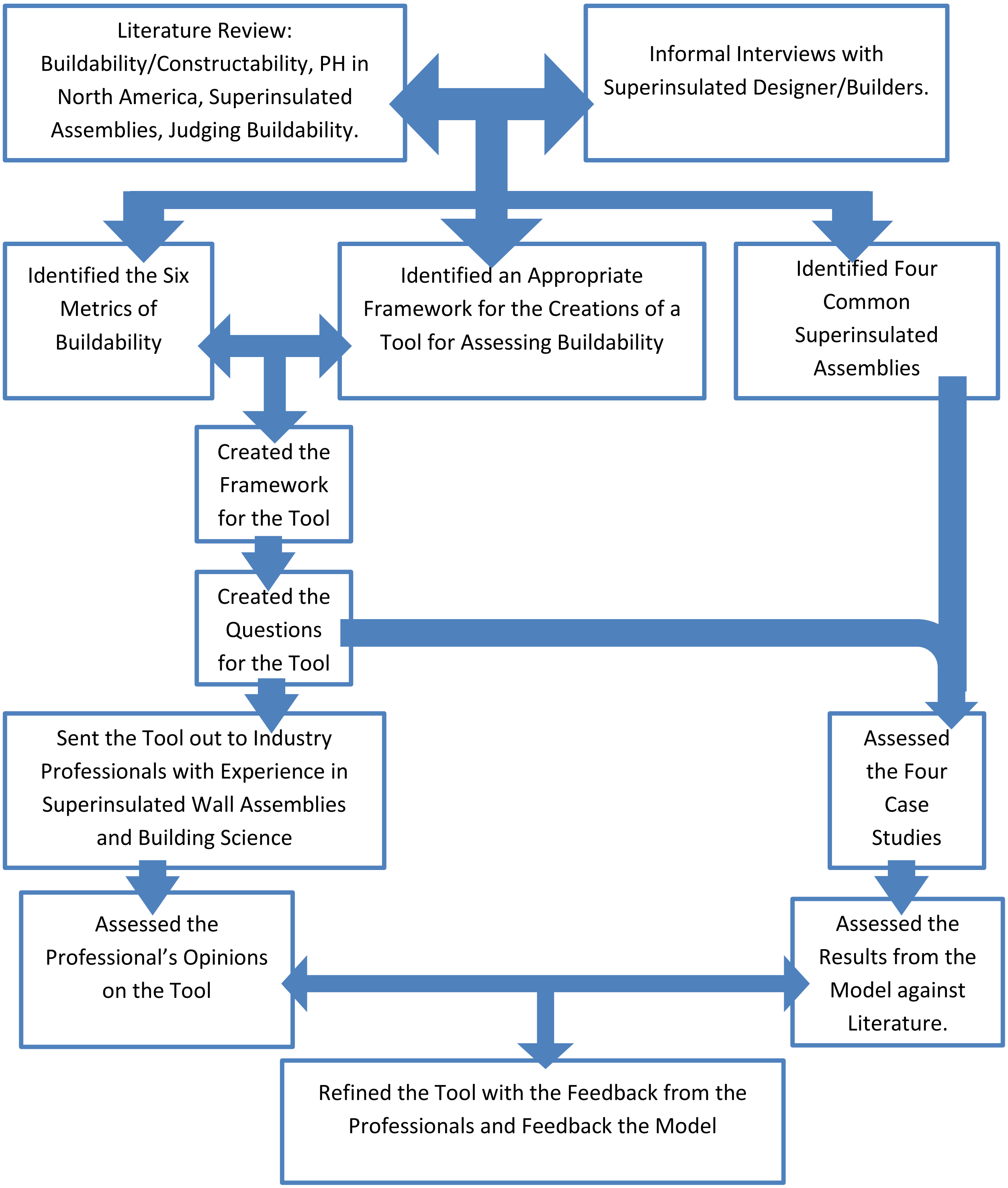
There is a clear need for this MRP's research, as shown by Straube's articles along with others discussed in the literature review. As Wong states in reference to buildability in the United States, "No scoring system has been established. Therefore, it is not possible to directly measure the buildability of a project"(2007).

It has been identified that Porter's 5 Force Model (Thompson, Peteraf, Bambe, & Stickland III, 2012), which relates directly to the assessment of market attractiveness, could be altered to create a tool for the assessment of buildability. As in the 5 Force Model, each metric of buildability could be weighed against each other equally, providing a general conclusion in terms of buildability of each assembly. The accessibility and simplicity of Porter's model enables the creation of an equally accessible and simple tool for assessing buildability in superinsulated wood framed assemblies.

CHAPTER 3: METHODOLOGY

3.1 Process Chart

The below methodology was followed in the creation and revision of the assessment tool in this MRP.



3.2 Collection of Data

Wong (2007) identifies five methods used to judge constructability, but Wong's methods—targeted at large-scale structures in Hong Kong—are not appropriate to the North American PH context. Wong used structured interviews with industry practitioners to determine what they believe to be the most important factors related to buildability; he developed his model for Hong Kong from those results. Straube and Smegal used a similar but less formal method for their research. According to Smegal (2014), they brought together five industry professionals with experience working with high-R value walls, and they conducted a conversation in which the merits of each assembly were weighed against each other. During this conversation, buildability was only one of the five areas under discussion. No specific metrics for buildability in context were identified, and the results are highly subjective and only useful when comparing one assembly to another. Finally, Straube and Smegal did not look at specific examples of these assemblies, but rather they considered and assessed only the general features of each assembly; however, there is wild variation with regard to the way some of these assemblies could be implemented, and these variables are not addressed by Straube and Smegal's assessment.

Because of the constraints of time and ethical approval, hosting formal interviews with industry professionals from across North America was unrealistic within the scope of this MRP.

The data for this MRP was collected through informal interview with industry experts who were experienced in designing and building superinsulated assemblies. This was conducted in a similar manner to Straube and Smegal's work, but over the phone. However, these interviews were focused specifically on buildability and identifying the metrics that affect buildability. A literature review was also undertaken on the following topics:

- Interpretation of Buildability and Constructability
- Passive House in North America
- Superinsulated Wood Framed Assemblies
- Judging Buildability

The interviews and literature review generated a significant amount of data related to the construction of superinsulated wall assemblies made of wood, and the factors that affect their buildability. In Chapter 4 the metrics that affect buildability are be identified from the data. The identified metrics are then used towards the creation of questions to assess the buildability of the assemblies, in keeping with Porter's 5 Force framework. To assess the tool, the preliminary model (Appendix I) was given to a group of industry professionals; their comments are included in Chapter 6.

CHAPTER 4: TOOL DEVELOPMENT AND PREMIMINARY APPLICATION

4.1 Identifying Metrics

4.1.1 Interview Results

Three industry experts who design and construct superinsulated wall assemblies were asked their opinions regarding buildability and the factors that affect it.

Adam Cohen is a designer/builder focused on the commercial side of Passive House. Cohen uses prefabricated walls built in a factory off site. His method of creating a superinsulated wall involves a 2x4 stud structure with exterior insulation consisting of ether EPS or Rock Wool. His method stresses the importance of experience, knowledge, quality and repeatability (Cohen, Judging Constructability, 2014). Cohen also stressed the one thing that came up throughout the research for this project: “Make it simple.” Cohen has taken the approach of many European PH manufacturers and taken the majority of his construction off-site.

Peter Amerongen is almost a household name in Canada. His Riverdale House (CMHC, 2014), a part of the larger Equilibrium project from CMHC, gained notoriety as a NetZero duplex at high latitude in a cold climate. Amerongen is a designer/builder who uses an advanced framed double stud wall system for his buildings. Amerongen believes that, the closer a building can be to standard practice, the better. He is focused on making his buildings as similar to conventional code buildings as possible. “Nothing difficult,” said Amerongen. “Only the framer has to change; all other trades do their traditional work” (Amerongen, 2014). He does some on-site training with the framers, to make sure they understand advanced framing and the double stud wall system. Amerongen takes emulating standard practice a step further. He uses a double stud system for his walls, the only system used for superinsulated walls which is built and insulated without the use of scaffolding or a crane. Amerongen’s method is to use platform framing where walls are built on a deck, walls are tipped up and then the next deck is built on top of the standing walls. This is the same method used in standard practice and because this method reflects standard practice Amerongen has made the construction of the wall more buildable.

Natalie Leonard is a Passive House designer/builder from Halifax. She has tried many wall assemblies, but the one she uses most is a traditional 2x4 or 2x6 stud wall for structure, with vertical TJIs bolted to the exterior. Leonard uses a vertical TJI as a truss in an assembly similar to a Larsen truss, which can limit thermal bridging at the second floor rim joist and can be continued down to overhang the top of the foundation wall; this enables her to improve and insulate the connection between the sill plate and the foundation.

The themes that emerged from the interviews with the experts have formed the basis for the six metrics used in the tool. Ultimately, each of the experts in their own work has done their best to relate their superinsulated assemblies to standard practice, which shows the importance of a consideration of the *working methods* used by the trades. Each of the experts already independently tries to make their method of construction an incremental step from what the *trades* practice every day, modifying the same methods and using *materials* that are known locally. The experts also each believed that the quality of the envelope and the air barrier systems installations in particular were paramount to the *success* of the structure. Training the trades was something each of them identified and Cohen in particular spoke of the importance of repetition and experience (2014). They each identified the importance of the working *drawings* and of ensuring that the instructions were clear and explicit in the design details, leaving nothing to change or interpretation. To recap, the experts identified the following: the importance of the trades, their experience with the assembly and the materials; the working methods the trades employed and relating those methods to the new assembly; the importance of the working drawings; and, a focus on quality to increase the potential for success in the assembly. Finally, Amerongen was the only expert to discuss cost. He saw the equations as the affordability of the build over the quality of the build (2014). Cost can be measured many ways, but for the purposes of this MRP cost will be related to the increase in *time and components* when compared standard practice. Thus the six metrics of assessing buildability were identified first as a result of a synthesis of the expert input at the informal interview stage, and then—as Section 4.1.2 will show—by referring to the literature to corroborate the experts' opinions.

4.1.2 Literature Results

Much of the work in the literature review identified the same factors as the experts. Straube and Smegal (2012) identify a series of issues that directly affect an assembly's buildability. They included a wall's susceptibility to moisture problems, the importance of quality workmanship, and the trades and their knowledge and experience with superinsulated assemblies. They also considered the complexity of the design, the amount of change from standard practice, the quality and clarity of the design details, the cladding attachment, and the time and components required to construct an assembly, as compared to standard practice.

Wong (2007) identified many of the same factors as well as some new ones. They included the design or shape of the building, the quality of the workmanship, the ease of construction as it compares to standard practice, and the efficiency and economy of the construction methods. Wong (2007) also identified some site-specific factors that included the detail drawings, the equipment required for the construction, the materials and their availability, the sequencing of the construction and the trades, the standardisation of constructions practices, and the installation of materials such as insulation.

Boqvist (2010) identified seven factors that effected constructability in wood framed PHs in Sweden. The factors effecting buildability in the list included building documents, construction planning, working methods, quality control, leadership, and the attitudes of the trades towards the project.

In their article, Aldrich et al (2010) identified the size and the weight of materials as a significant factor related to buildability. Heavier materials are more cumbersome to work with and often require heavy machinery to move or to set in place on a project. They also identified time, building shape, similarity to convention, workmanship, fasteners, and insulation installation as factors affecting a project's buildability. Broniek et al (2010) identified many of the same factors affecting buildability and specifically highlighted construction details and their importance around doors and windows in superinsulated walls to ensure these penetrations are tied into the air management and moisture management systems.

Thus, although they may have grouped the factors that affect buildability in different ways, each of these important studies confirmed the importance of the same metrics of assessing buildability that were identified by the experts.

4.1.3 The Context Spectrum

When trying to extract usable metrics for buildability from the list of those identified by both the experts and the literature review, a theme related to context began to emerge. The factors affecting buildability seem to fall on a contextual spectrum. Some factors were affected by the context of the location. This context included aspects such as the climate and the availability of materials. Since much of buildability is related directly to standard practice, metrics falling under the location context must be measured related to the standard practice of that location.

Another place on the spectrum of context was project specific. The metrics that were project specific look at specific aspects of only the project being assessed. For example, in terms of the framers working on a superinsulated assembly, standard practices of the location is less relevant to the buildability of a double stud wall—for example—than the framing crew's experience with double stud walls. If the framing crew has no experience with double stud walls, then—in terms of context—the buildability as it relates to the crew can be judged against standard practice. However, if the crew is well-versed in double stud wall construction and this is their tenth double stud wall build, buildability is related directly to the context of the question, "What is standard practice for this framing crew?". In this case, the buildability of a double stud wall would be far higher because of the crew's significant experience with this assembly. Each metric is affected by context differently. The key then is to identify the context which is most relevant to the metric being assessed.

The six metrics identified by both the industry experts and the literature were as follows: **working methods** (as it relates to the methods of consturction common to the location of the build, in which all of the trades in the area understand their roles and are comfortable with them), **time and components** (as it relates to standard practice and an increase in the time or number of components over the local common building methods), **the potential for success** (as it relates to any additional details which may be requried for an assembly, and that assembly's susceptibility to deficiencies—specifically assemblies which are known to collect water), **detail drawings** (as in the quality, clairity and completeness of the working drawing for the project), **trades** (specifically those that have been hired to do the work on this project and their experience, workmanship and knowledge as it realtes to the specific assembly) and **materials** (as they relate to the project: are they common to the trades? are they readily available? are they heavy? do they require additional equipment to move or install them?). The next step in the creation of a tool for assessing buildability is to clearly define these metrics of buildability, and from there, create questions to identify buildability as it relates to the specific metrics, in an assembly.

4.2 Factors Affecting Buildability (Metrics)

As with the example of Porter's 5 Forces, each of the six buildability metrics requires a series of questions so that they might be assessed. In this chapter, the questions will be created for the six metrics, to determine the ease or difficulty of that assembly's construction. Two of the metrics—trades and materials—cannot be assessed because they are site-specific and context-specific. However, questions which would assess their buildability in context will be proposed, so that a user with the knowledge of local trades and materials can incorporate these factors in his or her assessment.

4.2.1 Working Methods

The "working methods" of a project as related to buildability will rely on general deviations from standard practice. The interviews along with the literature agree that one of the most important, if not the most important, factor in buildability is the idea that standard practice is "perfectly constructible" (Wong, 2007). Leonard put it best, "What is everyone used to?" (2014). The most buildable assemblies will be those that are closest to what people are familiar with doing every. Most PHIUS projects are one-offs. Of those, a common structuring of the project is to use the designer/builder model of construction. The importance of the trades and their skills and knowledge will be discussed in the 'project specific context' portion of the metrics; however, if a crew has experience in constructing a superinsulated assembly, this can be a significant asset. The designer/builder model bridges the gap that can be so detrimental to buildability: the fact that designers often do not understand how their designs will be implemented on site. This leaves the possibility of the details being incorrect, misused or ignored all together. In a PH project, poor implementation of details could have devastating effects in terms of the air tightness and moisture management.

Boqvist (2010) identifies "working methods" as one of the key areas identified within PH construction: "Seven focus-areas within passive house construction have been identified as key areas: System design, Building documents, Construction planning, Working methods, Quality controls, Leadership and Attitudes" (Boqvist, 2010). He goes on to state, "There is a need to find alternative production methods which prioritise the product quality in an integrated and efficient manner" (Boqvist, 2010). Boqvist is saying that how these projects are put together is as important as their design because the ultimate success of the building—measured in energy savings, durability, cost and other factors—is determined by how a building is built. The *ease* of that process is its buildability.

The following questions are proposed for the Working Methods metric.

1. Deviation from standard practice: “Does the assembly reflect a traditional code built stick frame wall assembly?” This question essentially identifies the seminal factor in buildability. The closer a structure is to standard practice, the easier it is to build (Straube & Smegal, 2012).
2. Lumber: “Are the pieces used in the assembly of the dimensions used in common practice?” A part of standard practice is the materials which are being used. 2-by construction is common practice in much of North America, and therefore deviation from those dimensions in cases where those dimensions are common would be less buildable.
3. Fasteners: “Are components attached using practices common to those constructing the assembly?” Nailing, whether by hand or with a gun is common practice in much of North America, though there are places where screws and bolts are common practice. If in the context of the location nails are common practice and bolts are required in the working drawings, this would be considered less buildable.
4. Insulation installation: “In the insulation used common and is it applied in the usual manner?” Different insulations are common to different parts of North America. The insulation used in the structure must therefore be compared to the common insulation used in the local context.

4.2.2 Time and Components

The “time and components” metric will look at the time difference between standard practice and the superinsulated assemblies, as well as the difference regarding the number of components. The time factor will be taken from literature, where much work has been done comparing standard practice against the increased time taken to build superinsulated assemblies (Broniek, Brozyna, & Stecher, 2010) & (Aldrich, Arena, & Zoeller, 2010).

For comparison, it is useful to specify a base case—an example of the local standard practice. The base case in the examples used in this MRP will take the form of an Ontario Building Code (OBC) standard practice SB-12 wall measuring 8’x8’, which consists of:

- 10, 2”x6” studs @ 16” o/c (pin, spruce, fir)
- 2, 4’x8’ sheets of sheathing (plywood or OSB)
- 2, 4’x8’ sheets of gypsum board
- Batt insulation
- 64 sq ft of 6-mil polyethylene
- 64 sq ft of spun-bonded polyolefin (SBPO)

In terms of components, the studs can be measured in cubic feet of wood; in this base case, the total is 4.4 cubic feet:

- Studs consist of 3.06 cu ft
- Bottom plate and two top plates consist of 1.38 cu ft

In the case of the vertical TJI assemblies, the TJI will be measured in “story height lengths”.

Sheet stock will be measures by the sheet, meaning that for the wall described above, two sheets of sheathing and two sheets of gypsum are required. Insulation will be measured by the cubic foot. In the base case application the insulation is 29.3 cubic feet. The poly and the house wrap will be measured in 64 square foot sections. The weight of the assembly will also be determined.

The following questions are proposed for the Time and Components metric. Many of the questions are in response to Broniek et al’s claim, “For a wall system to achieve the highest score for (buildability)… it must require fewer parts” (2010).

1. Time: “Does assembly require additional time?” Additional time as a factor in the buildability of a wall assembly was identified by Aldrich et al (2010) along with many of the other papers such as Wong (2007) and Broniek et al (2010). If something takes longer to build, it is therefore less buildable.
2. Wood: “How many cubic feet of wood are required in an 8x8’ section of this assembly?” The additional weight and number of components decreases buildability as identified by Broniek et al (2010).
3. TJIs: “What is the spacing of the TJIs in an 8x8’ section of this assembly?” TJIs are a unique case as there is no place in North America where they are standard practice. The more TJIs, the greater the weight; the more components that go into a wall, the less buildable the assembly is.
4. Sheathings: “How many sheets of sheathing are required in an 8x8’ section of this assembly?” The greater the amount of sheathing, the greater the amount of work.
5. Insulation: “How many cubic feet of insulation are required in this assembly in an 8x8’ section of this assembly?” More insulation requires more time to install.
6. Membrane: “How many membranes are required in an 8x8’ section of this assembly?” Membranes are vitally important in a superinsulated assembly as mentioned earlier. They require time, patience and skill to be applied correctly, all which will affect a structure’s buildability.

4.2.3 Potential for Success

The “potential for success” results will be derived directly from the literature. This metric will take into account whether additional details are required, and will consider an assemblies’ susceptibility to deficiencies. Finally it will identify the potential success of its connections.

The following questions are proposed for the Potential for Success metric.

1. Additional details: ”Does the complexity of the assembly require additional details?” It was identified by Aldrich et al (2010) that some superinsulated assemblies such as exterior insulation require additional details for penetrations such as windows and doors to ensure that the assembly is draining away from the building properly. Other superinsulated assemblies such as a double stud wall would simply follow best practices of a standard practice wall. The details associated with exterior insulation would therefore be less buildable, whereas the details for a double stud wall would be more buildable because they follow standard practice.
2. Susceptibility to deficiencies: “Is this assembly known for its susceptibility to failure?” (i.e. collecting water). The major problem with superinsulated wall assemblies is their potential to collect water, as mentioned above. Some superinsulated assemblies are less likely to do so than others, such as exterior insulation (which allows from drying towards both the interior and the exterior). An assembly with these characteristics obviously has a higher potential for success.
3. Connections: “Are the connections between components reliable, supported, redundant and effective?” The importance of connections was identified by Leonard (2014). Her system includes a Larsen truss that continues past the sill plate and down over the foundation wall. F.P. Innovations (2013) also identifies the importance of supporting connections. Redundant connections are standard practice in many wood framed PH in Europe (La Vardera, 2010).
4. Code: ”Is the wall code compliant?” Compliance with code was identified by Smegal (2014) in reference to the success of getting a superinsulated assembly approved by the local building authority.

4.2.4 Detail Drawings

Moving on to the metrics looking at context, “detail drawings” will look at the quality of the working drawings, noting especially the clarity of the information they relay. In order for a Passive House to be buildable, details must be supplied for each of the following situations:

- Window/door header
- Window/door casement
- Window sill
- Foundation/slab meets wood framing
- Wall meets second floor
- Wall meets roof
- Outside corner
- Inside corner

As well, to be considered ideally buildable, the details must contain explicit written instructions regarding how the assembly will go together, noting both(1) the sequencing/placement/lapping of membranes and (2) the integration of flashing around wall penetrations and into the barrier or rain screen system.

The following questions are proposed for the Detail Drawings metric.

1. Barriers and retarders: "Are all barriers/retarders visible in the details including clear instructions as to their sequencing in the assembly and the application?" This question is directly related to the importance of accurate working drawings and leaving nothing in the drawings up to interpretation. The importance of accurate and comprehensive working drawings was identified by Boqvist (2010).
2. Continuity: "Is the continuity of the insulation and the membranes addressed visually and in written form in the details? Is the insulation within the same plane?" Though this falls under the detail drawings in general, this is a performance aspect of the assembly.
3. Simplicity: "Have the details been simplified to exaggerate the most important aspects of the construction?" Cohen (2014) identified the importance of making the details clearer than they would be in typical working drawings.
4. Required details: "Are there specific details for all of the following which apply? Window/door header, window/door casement, window sill, foundation/slab meets wood framing, wall meets second floor, wall meets roof, outside corner, inside corner and penetrations". The preceding is a list of the common detail drawings associated with an assembly.

4.2.5 Trades

A vitally important aspect of the ease of construction is connected directly to the trades working on the project. The “trades” metric will look at the knowledge, the experience and the attitude of the tradespeople involved in a project. This can have a significant impact on the success of a project. As stated above, most North American PH projects are one-offs in which the designer/builder method of construction is dominantly used; thus, the gap between the designer and the builder—which can be so detrimental to buildability—is often bridged. This method is equally relevant for non-PH superinsulated projects.

The following questions are proposed for the Trades metric.

1. Experience: “Have the trades worked with this method before? Do they have experience using advanced framing?” Cohen (2014) and Amerongen (2014) both identified the experience of the trades with the specific assembly type, as well as experience with advanced framing as important aspects of buildability for their assemblies.
2. Education: “Are the trades educated regarding building envelopes and energy efficiency?” Education is an important factor in the success of a superinsulated assembly. “(L)etting the construction workers participate early in the process, e.g. through education, together with continuous information about the project during construction, has shown to be factor of success in Passive House construction” (Boqvist, 2010).
3. Inclusion: “Were the trades included in the design process? Is there an open line of communication between the trades and the designer/consultant?” The importance of inclusion is stated in the Boqvist (2010) quote above and also by Holroyd (2003) who points out the obvious fact that no one knows the jobs of the trades better than the trades themselves; this knowledge can be an assett towards making a project more buildable.
4. Workmanship: “Do the trades have high standards of performance?” Each of the experts and much of the literature identified air sealing as the most important aspect of constructing a superinsulated assembly. Without tradespeople performing to a high standard, reaching the required air tightness for a PH would be impossible. “(P)rofessional qualified staff during the execution phase (of construction) and persistent construction supervision… include the increased requirements for the building shell with reference to heat insulation, protection against moisture, structures without thermal bridges, and air tightness” (Ringer, 2011).

4.2.6 Materials

The "materials" metric will relate specifically to the region where the structure is being built. Are the materials required common in this area? Are the trades experienced in working with them? As well, it will look at the size and weight of the materials. Does their size make them awkward to work with? Do they require additional equipment for their installation, such as a crane?

The following questions are proposed for the Materials metric.

1. Availability: "Are the materials available in your area?" If materials are not readily available in the area where a building is being constructed, this is a potential detriment to buildability.
2. Experience of the trades: "Are the local tradespeople familiar with working with these materials?" The best example of why this question is so important comes from the use of fiberboard as the exterior sheathing in a vertical TJI assembly. This material is not in common use in much of North America, and using a material that is new to the tradespeople requires a learning period. Holladay (2013) give two examples of framing crews which encountered problems with the fiberboard bulging after the walls were insulated. A team experienced with fiberboards would know that the sheathing was not as rigid as OSB or plywood.
3. Cumbersome: "Are the materials larger or heavier than those traditionally used on site?" The weight and size of materials can have a significant effect on the ease with which they are moved. Larger, heavier materials require more workers to set in place. They may also take up more space on a site, which can be significant when working on a small lot.
4. Machinery: "Does the application of these materials require any additional equipment such as scaffolding, a crane or a blower for cellulose which is not used in standard practice?" Additional equipment and machinery add to the cost of a project and cause a project to travel further from standard practice. The double stud wall is the only assembly assessed in the MRP which can be platform framed without a need for scaffolding or some other additional equipment to assemble the structural wall with its insulation. Scaffolding would likely be required for the application of the façade on all wall assemblies.

4.3 Discussion of Superinsulated Assembly Issues

In this section, exterior insulation, double stud wall, the Larsen truss and vertical TJI will be analyzed for the following: positive attributes, buildability, problems with buildability, and construction method. These four factors relate directly to the six metrics identified above. After identifying the strengths and weaknesses of the assemblies in general, a case study for each assembly will be assessed using the tool created in this MRP. The results from the tool will then be compared to the factors identified here to determine whether the tool is effective in identifying positive and negative attributes of the four assembly examples.

4.3.1 Exterior Insulation – Jackman Residence

Exterior insulation is a method of superinsulating a wall: it involves attaching insulation to the exterior structural sheathing (usually plywood or OSB). In a wood framed assembly, the structure is generally supplied by a 2-by stud wall on the interior. This internal framing can be spaced at the conventional 16" on center; however, many designers are choosing to use advanced framing techniques that require framing at 24" on center. In the case of exterior insulation, the insulation itself is either a rigid board such as EPS or XPS, or a rigid batt such as Roxul Comfortboard.

The Jackman Residence is a Passive House project in Vermont, built in 2012. The superinsulated wall is constructed in an exterior insulation assembly.

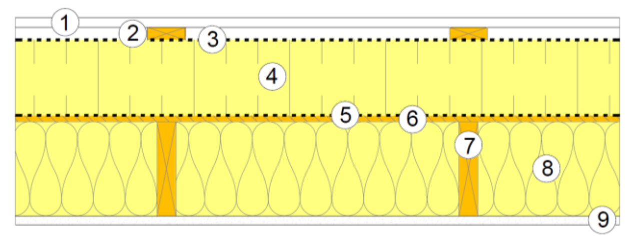


Figure 4: Wall section detail of the Jackson Residence in plan view (exterior insulation).

	Elements of a Typical Exterior Insulated Assembly	Jackman Residence
1	Exterior finish	8.25" fiber cement clapboard
2	Strapping (for exterior insulation thicker than 1")	1" vertical wood strapping
3	Weather barrier system	(see below)
4	Exterior insulation (rigid batt or board)	6" foil-faced polyisocyanurate rigid insulation, all joints staggered, gaps foamed and seams taped over
5	Vapour retarder (or can be placed further inboard)	Huber zip system
6	Sheathing	0.5" wall sheathing with all seams taped with manufacturer's recommended tape
7	Structural framing	2"x8" stud wall @ 24" O/C
8	Insulated stud cavity	7.5" of dense-pack cellulose
9	Gypsum board	0.625" gypsum board

4.3.1.1 Exterior Insulation Discussion

POSITIVE ATTRIBUTES:

Exterior insulation is a popular method of superinsulating for many reasons, but specifically its performance and its buildability:

> *In cold climates, insulation placed on the exterior of the stud wall increases the temperature of the moisture-sensitive wood sheathing and framing, and reduces the risk that condensation will occur due to air leakage and vapour flow from inside. Such a wall assembly may therefore have improved durability performance over traditional interior-stud-insulated wall assemblies* (F.P. Innovations, 2013).

If an assembly were to have a leak in its air barrier system, moisture-laden air travelling through the interior insulation and reaching the sheathing would experience less of a temperature drop as compared to a conventional wall or even other forms of superinsulated assemblies that have exterior sheathing. Because the sheathing in an exterior insulated wall (or a "split-insulation assembly," as they are sometimes called) is sandwiched between the stud cavity insulation and the exterior insulation, the temperature of the sheathing remains warm enough to limit the potential for condensation to collect. Warm sheathing protects the studs and sheathing from damage by preventing moisture buildup that causes mold and rot in materials which are susceptible to these failures.

It is common practice in superinsulated projects to increase the air tightness of the building envelope which in turn saves energy. However, in the case of exterior insulation, the potential havoc wreaked by a leaky air barrier is not as great a concern in terms of durability as in many other superinsulated wall assembles. Because an exterior insulated assembly can dry outwards, and because it has sheathing which is warm enough to prevent condensation, water in unlikely to accumulate in the wall cavity, protecting the structure from mold and rot (Aldrich, Arena, & Zoeller, 2010).

As well, in terms of performance, exterior insulation can have a limiting effect on thermal bridging:

> *Because of the continuous insulation over the exterior of the framing, the thermal bridging from the framing becomes negligible and, therefore, the framing factor becomes much less important where the overall wall R-value is concerned. Advanced framing becomes about cost savings and material conservation as opposed to overall R-value* (Aldrich, Arena, & Zoeller, 2010).

Basically, by adding insulation to the exterior of the structure, the interior insulation is less affected by the thermal bridging from the structural elements and, therefore, the R-value of the interior wall assembly increases. This is a “win-win” situation: the addition of insulation on the exterior of the building actually increases the value of the interior insulation and is one of the many reasons building science professionals are singing the praises of exterior insulation.

BUILDABILITY:

In terms of buildability, the exterior insulation assembly has many positive attributes. The structure or framing for this type of assembly requires very little from a standard framing crew: “Added blocking may be needed for various penetrations and the builder may choose to employ advanced framing techniques, but no major changes to conventional practices are necessary” (Aldrich, Arena, & Zoeller, 2010). As mentioned previously, advanced framing is often used in these walls, but more from the standpoint of cost and material savings as opposed to limiting thermal bridging, which is one of advanced framing’s main characteristics. Even if advanced framing is employed, framers will only require minimal training (Aldrich, Arena, & Zoeller, 2010).

The deviations from standard practice are there, however:

> *Continuity of the water-shedding surface is more critical in wall assemblies that utilize XPS insulation. Window sub-sill drainage should direct water to the exterior side of the XPS insulation.* (F.P. Innovations, 2013)

The detail drawings must address these concerns. In the case of exterior insulation assemblies, additional drawings must be included, focusing on the installation of the exterior insulation, the windows and the flashing/drainage layer.

PROBLEMS WITH BUILDABILITY:

The major draw-back of exterior insulation assemblies in terms of buildability concerns windows and doors:

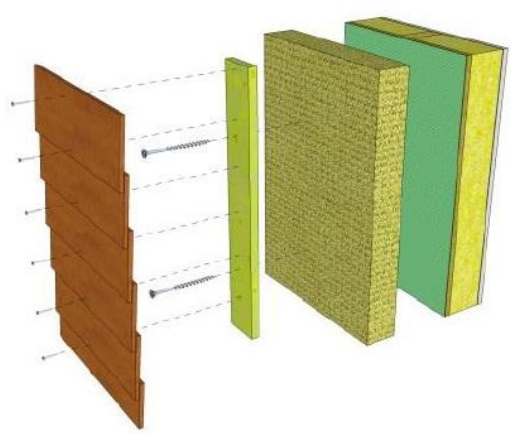
> *Windows can be installed either at the plane of the exterior structural sheathing (interior mount or inset) or at the outer-most plane of the rigid insulation (exterior mount or outset). Each configuration poses its own challenges and must be flashed and tied into the drainage plane in a different way* (Aldrich, Arena, & Zoeller, 2010)*.*

Windows especially are a potential weak point in a wall system. It is particularly difficult to flash a window when integrating exterior insulation because there are situations where mechanical fasteners cannot be attached through the insulation. Careful sequencing must be followed, as the flashing needs to precede the installation of the exterior insulation, and the exterior insulation has to be modified to accommodate the flashing. As Aldrich (2010) notes, meticulous detailing regarding windows in particular is thus of vital importance; he also identifies related challenges concerning doors and mounting flanges.

CONSTRUCTION METHOD:

As mentioned above, there are two common types of exterior insulation: semi-rigid batt and rigid board insulation. Each has their advantages, but rigid board insulation is what is most often recommended for this type of application, because mechanical fasteners that hold up the insulation and the cladding will fail if insufficiently supported by a rigid board.

Attaching to the structure through a rigid board as opposed to a semi-rigid batt is more buildable and has the potential for a more consistent finish. Any exterior insulation thicker than 1" must be supported by strapping so that the cladding has something to attach to (Broniek, Brozyna, & Stecher, 2010). This strapping is generally a 1x3 placed on the exterior of the insulation and drilled through into the structure, whether that be the sheathing beneath or the studs beneath, as shown in Figure 11 (F.P. Innovations, 2013).



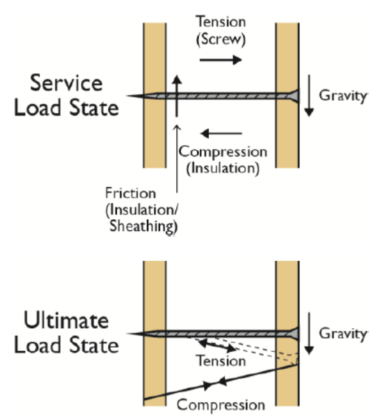


Figure 5: Exterior insulation wall assembly (left), and forces acting on mechanical fasteners attaching rigid insulation (right) (FPInnovations, 2013).

What this means for exterior insulation is that a long, thin screw is supporting the weight of the strapping, the insulation and the exterior cladding. FPInnovations (2013) and Aldrich (2010) both suggest that, for superinsulated buildings, semi-rigid exterior insulation is too compressible to enable the long, thin screws to support the cladding. FPInnovations explain in detail the considerable tension that the screws are under; Aldrich recommends that the rigid board be made of polyisocyanurate (polyiso, R6.5/inch), expanded polystyrene (EPS, R4/inch) or extruded polystyrene (XPS, R5/inch) (Aldrich, Arena, & Zoeller, 2010). Though these foam boards are in common use, they can limit an assembly's ability to dry outward and can caused moisture to be trapped within the assembly. The two alternatives are either to use a rock wool type board which has a higher vapour permeability, or to eliminate the interior vapour retarder and ensure that the walls will not be covered in vinyl wallpaper to allow the wall to dry inward (Turns, 2011).

If the rigid insulation is to act as the drainage plane for a rain screen system, it is essential that all of the joints are taped and sealed, preventing water from moving past the insulation and becoming trapped against the sheathing (F.P. Innovations, 2013). Broniek (2010) has noted that the process of sealing and taping every seam in the insulation is labour-intensive and time-consuming. The solution, then, is to use an air barrier membrane instead of a taping individual seams:

> *The sheathing membrane is taped/sealed and sandwiched between the sheathing and the exterior insulation in this assembly, which addresses structural support. Applying a self-adhered or a liquid-applied vapour-permeable membrane to the sheathing would have comparable performance. Alternatively, a sealed-sheathing air-barrier strategy could be used. Continuity of this air-barrier membrane through details and interfaces is critical in terms of whole-building airtightness.* (F.P. Innovations, 2013)

CONCLUSION:

As has been shown, exterior insulation as a form of superinsulation for wood framed projects has some major advantages. The notable advantage in terms of buildability is that the system does not deviate dramatically from traditional framing techniques, though some minor education related to advanced framing may be necessary. The major difference between exterior insulation assemblies and standard practice is in the cladding. Two major questions for this manner of superinsulating an assembly are: who will apply the exterior insulation? And, do they have experience with doing so? In terms of buildability, the application of the exterior insulation will require scaffolding and explicit detailed drawings which must be followed to a tee, particularly around doors and windows.

4.3.2 Double Stud Wall – Tree Eco-Village

The double stud wall assembly consists of two sets of walls built parallel to each other. The concept is that, by eliminating a continuous stud running from the exterior sheathing to the interior gypsum, a major thermal bridge is broken. Double studs allow you to increase the thickness of the wall using traditional framing elements, making the assembly closer to standard practice. As well, this assembly has the possibility for a "chase cavity" if polyisocyanurate is used and attached on the outboard side of the interior stud assembly. This chase will make a home more airtight by limiting penetrations through the membrane for electrical, plumbing and HVAC. The most common insulation in a double stud wall is densely packed cellulose (Robb Aldrich, 2010); however, batt insulation and rigid foam, or even a layer of spray foam, are not uncommon.

The Tree Eco-Village home is a Passive House design from New York State, built in 2012. The superinsulated wall is constructed as a double stud wall assembly.

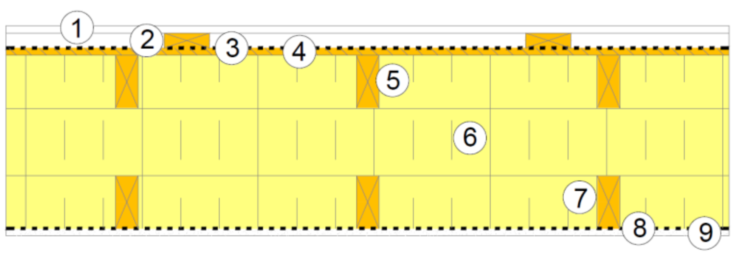


Figure 6: Wall section detail of the Tree Eco-Village home in plan view (double stud wall).

	Elements of a Typical Double Stud Assembly	Tree Eco-Village
1	Exterior finish	0.5" fiber cement panel or ribbed metal siding
2	Strapping	1x3" furring strips
3	Weather barrier system	Tyvek Wrap
4	Sheathing	½" OSB
5	Exterior stud wall	2x4" stud wall @ 16" O/C
6	Cavity insulation	11.5" open-cell foam insulation (R-42)
7	Interior stud wall	2x4" stud wall @ 16" O/C
8	Vapour retarder (or can be placed on the outside of the interior stud wall).	Intello air/vapour barrier
9	Gypsum board	0.5" gypsum board

4.3.2.1 Double Stud Discussion

POSITIVE ATTRIBUTES:

Though this method does save wood compared to an assembly of this thickness using deep studs, two walls must be constructed and therefore it takes more time, relatively. However, as noted in one of the studies, for a double stud wall, only the interior of the interior studs and the exterior of the exterior studs must be lined up (Broniek, Brozyna, & Stecher, 2010). This could in fact make a double stud wall more buildable than a deep stud wall, as deep studs are more difficult to work with and are more likely to be warped; when creating a deep stud wall it is essential that both the interior and exterior of the studs are lined up correctly on the plates, which was noted to take additional time (Broniek, Brozyna, & Stecher, 2010).

One of the solutions to the additional time and materials associated with a double stud wall has been to use advanced framing techniques, which can reduce material and labour. Advanced framing does require more careful planning, but it can significantly reduce the amount of lumber in a wall. As well, of the two walls assembled, one is not load-bearing and therefore requires much less structure. The non-load-bearing wall should have a single top plate and be framed on 24” o/c. As with the exterior insulation assembly, advanced framing’s real advantage in this application is not limiting thermal bridging but rather saving wood (Aldrich, Arena, & Zoeller, 2010).

The potential to reduce the framing factor is there—it just has less effect on the thermal efficiency of the wall because of the large thermal break in the center of the wall. Therefore the “win” in terms of advanced framing in this application is related to the cost savings in labour and material.

BUILDABILITY:

Buildability in a double stud wall assembly is fundamentally very similar to standard practice. One example of a double stud wall assembly is the “Deep Wall System” (DWS) used by Peter Amerongen in the Riverdale House (a superinsulated NetZero residence built in 2008) in Edmonton, Alberta. Essentially the DWS is a double stud wall with spacing at 24” o/c on the interior wall and 16” o/c on the exterior structural wall. The cavity is filled with cellulose, and a vapour retarder is applied on the inside of the interior wall (CMHC, 2009).

> *The Riverdale NetZero DWS requires no deviation from the typical construction sequence. The builder reports a number of labour management benefits for this super-insulated wall:*
>
> - *Maintains traditional trades work sequence;*

- *Additional labour costs only for framer and the insulator; and*
- *Plumbing and electrical services easier to run through the wall cavity with fewer holes needing to be drilled* (CMHC, 2009).

Amerongen (2014) also pointed out that, unlike many of the other methods related to superinsulating, the double stud wall system is erected in a manner which does not require scaffolding. The lack of scaffolding means that double stud wall assemblies are closer to standard practice in regards to the raising of the walls; all other assemblies discussed in this project do require scaffolding, either for the application of the insulation in the case of exterior insulation or for the application of framing in the case of the truss wall and the vertical TJIs.

One of the major advantages in terms of buildability for a double stud wall is related to the exterior finish, in that it is “very similar to that of conventional framed wall systems” (Aldrich, Arena, & Zoeller, 2010). As well, the details related to a double stud wall are similar to those used in the average code-built structure.

> *To builders of conventional stick-framed homes, often one of the most appealing features of double wall systems is that there are very few new exterior details. Exterior sheathing, structural bracing, house wrap or building paper, window and door flashing, and siding attachment are usually identical to good details in conventional, framed wall systems* (Aldrich, Arena, & Zoeller, 2010).

The installation of fixtures in a double stud wall does not require the same meticulous detail drawings as an exterior insulation assembly.

While the framers are the only tradespeople whose job is altered by this type of assembly (Amerongen, 2014), the benefits of the decision to use a double-stud wall are spread amongst many of the trades, which thus increases the buildability of this assembly.

> *There are no significant changes that electricians need to make in double-wall homes. Electrical rough-in can be slightly simplified as drilling through studs is not necessary in exterior walls; wiring (in or outside of conduit) can be run between the two walls. Aside from careful coordination of wall penetrations mentioned above, there are few - if any - changes required of plumbers in double-wall homes.* (Aldrich, Arena, & Zoeller, 2010).

The ease of construction of this assembly is further increased by the fact that a double stud wall enables the creation of a space which makes the work of tradespeople such as electricians and plumbers easier.

There are concerns related to potential water condensing on the exterior sheathing as there is no insulation outboard of said sheathing. To address these concerns, the integrity of the interior air barrier system is paramount. For this reason the 6 mil. polyisocyanurate, which is common in cold climate assemblies in North America, may be replaced with either a layer of OSB or plywood, as both of these materials are dramatically more durable than a thin piece of plastic:

> *This approach is common in Europe and with pre-fabricated highly insulated walls. The plywood [or OSB] is sealed and joints are taped with special tapes designed for adhering to wood and to maintain adhesion and structure for the life of the building. The plywood [or OSB] also acts as the vapour retarder in this assembly, removing the need for polyethylene. An interior 2x4 stud wall is often constructed to the interior of the deep-stud wall in order to run electrical and plumbing services and thus avoiding any need to penetrate the plywood air barrier* (F.P. Innovations, 2013).

Though this method does increase the amount of materials in the assembly, the rigid sheathing has a higher potential for success as a retarder than would the 6 mil. polyisocyanurate. As well, with sheathing and tape method, a gap or penetration in the barrier—and therefore the potential for its repair—would be more obvious. The ability to identify such faults in the retarder would result in a tighter house.

PROBLEMS WITH BUILDABILITY:

There are serious concerns related to the durability of double stud wall assemblies. This type of assembly is very susceptible to damage due to water. The literature stressed the importance of detailing the air barrier system to ensure the assembly was air tight (F.P. Innovations, 2013).

Air sealing is therefore vitally important in this assembly, because if done poorly, moisture-laden air will enter the cavity. In the heating months, that air will condense on the exterior sheathing, causing water to collect. To reduce the risk of mold and rot, it is important to have a near-perfect air seal in a double wall assembly (Aldrich, Arena, & Zoeller, 2010). Tradespeople who recognize the importance of air sealing are also vitally important. This is an area in which training, knowledge and experience are significant factors in the success of said assembly.

Because the construction of two walls is required instead on one, the amount of time and materials required to construct a double stud wall is greater than that of a traditional wall. Though advanced framing can decrease the amount of lumber used, and though there is significantly less lumber used than would be if a wall of that thickness were to use a single stud in a deep cavity, the double stud wall is material intensive. The amount of material used in this assembly obviously increases if the OSB/plywood interior air barrier is used.

> *The additional time and material required for framing is the most significant and costly change from traditional frame construction. Because window and door openings in the inner frame wall must be carefully aligned with windows and doors, framing the interior wall can sometimes take more time than the exterior framing* (Aldrich, Arena, & Zoeller, 2010).

As has been stated many times in this project, deviation from standard practice is considered less buildable. In the case of superinsulated walls, the deviation is generally significant. In the case of double stud walls, however, despite the increase in labour for the second wall and the window bucks, this system is considered to remain relatively true to standard practice. However, the layout of the exterior wall can have a large effect on the buildability.

> *Planning for double walls is key, and complicated or convoluted building designs (many angles, curves, irregular dimensions, dormers, etc.) can dramatically increase the time and cost of double wall systems* (Aldrich, Arena, & Zoeller, 2010).

> *It's important to note that these [double stud wall] homes are usually very square, and they are designed for double walls. A conventional framed home with more corners, non-right angles, and relief requires substantially more framing time and material. When using double walls, this extra framing cost is at least doubled, so designers should be very conscious of the benefit of simple home footprints.* (Aldrich, Arena, & Zoeller, 2010)

Therefore, a double stud wall assembly is quite buildable if the building is a square or a rectangular in plan, but a complex building shape may result in a nightmare for a framing team.

One of the most common ways to insulate a double stud wall is with blown in cellulose. This method of insulating is quick: the insulation is simply blown into the cavity, and if the insulation is dense packed, settling is not a huge problem. However, if maintenance and repairs to the amenities inside the wall are needed, that maintenance becomes more difficult when the wall is filled with a loose insulation.

When an entire story of a home has a single 9-12" wall cavity filled with insulation, adding penetrations after walls are insulated is not straightforward. In conventional frame construction, rough-in for exhaust fans, plumbing, combustion appliances, etc. are installed before insulation. In double-wall homes, careful planning for these penetrations is even more important. (Aldrich, Arena, & Zoeller, 2010).

To prevent an avalanche of dense packed cellulose, it is advisable to block off areas which involve plumbing and HVAC inside the wall by creating a separate cavity for penetration and amenities (see Figure 12). If the wall is to be opened, the majority of the loose fill insulation will remain in place and only the small cavity which included the vents or piping must be opened and eventually re-insulated. Creating this type of cavity does require work and therefore takes time and costs money.

Figure 7: DWS blocking off penetrations (Aldrich, Arena, & Zoeller, 2010).

CONSTRUCTION METHOD:

A double stud wall is built in a very similar fashion to a standard code wall. It is platform framed—as many of these assemblies are—but requires nothing on the exterior which must be attached after the framing but before the exterior finish. The walls are built on the site in one of two ways: either build the exterior wall first and then add the second wall, or build the two walls as a single piece with a space between them and then stand the system upright and attach them to the subfloor.

Advanced framing can be used to save both time and wood in what is already a labour and material intensive assembly:

> *As the inner wall is not load-bearing, framing spacing can sometimes be reduced to 24" on center. With careful structural planning, framing in the exterior wall may also be reduced to 24" on center in some instances. On the inner wall, double top plates and jack studs are often not necessary (though jack studs may still be used for more consistent alignment of window openings). Two-stud corners are very simple to implement in on both the outer and inner framed wall, as no drywall is attached to the outer wall, and no exterior sheathing is attached to the inner wall* (Aldrich, Arena, & Zoeller, 2010).

CONCLUSION:

The double stud wall assembly does not deviate far from standard practice. It isn't too different from what most of the trades do every day, and that makes it buildable. Advanced framing can save time and material in this assembly. However, the number of wall assemblies constructed is doubled, which will increase time and materials. As well, there are significant concerts related to water collection in this assembly.

Proper and clear detailing of the air barrier and water-shedding systems is essential to the success of this assembly, as is the workmanship. All of the trades must be on-board, educated and dedicated to creating both an interior and an exterior air barrier which are continuous. Any penetrations must be red flagged and addressed before the wall is closed to ensure that water is directed outward and that penetrations are air tight. Failure in the air barrier systems seriously when using a double stud wall can have significant negative impacts on the durability of a building and the health of its occupants. The quality essential to this wall assembly's construction affects its buildability.

4.3.3 Larsen Truss Wall – Pedler Residence

A Larsen truss or standoff wall is generally an attached to the exterior sheathing of a structural wall with the intent of increasing the wall's thermal resistance. In 1981, John Larsen, who was a builder in Edmonton, developed this technique. His initial wall consisted of 2x2s connected with rectangular gussets made of 3/8" plywood (Holladay, 2011). These initial trusses were site built, but now many of the trusses used in this type of assembly are prefabricated off site. Today "Larsen Truss" is the generic name for any truss hung from a structural wall as a cavity to increase a wall's thermal resistance. These trusses are not load-bearing and carry none of the roof's weight.

The Pedler Residence is a Passive House design from Massachusetts, built in 2013. The superinsulated wall is constructed as a Larsen truss.

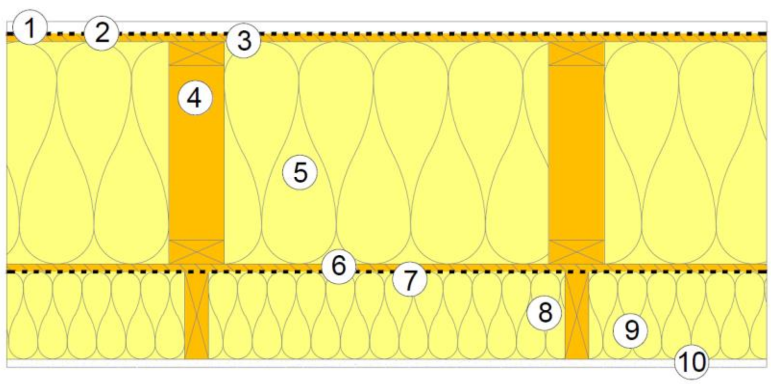


Figure 8: Wall section detail of the Pedler Residence home in plan view (Larsen truss).

	Elements of a Typical Larsen Truss Assembly	Pedler Residence
1	Exterior finish	0.75" cedar shingles or metal siding
2	Weather barrier system	2 layers of "Type D" building paper
3	Sheathing	0.5" plywood sheathing
4	Wooden truss	14" wood ladder truss @ 16" O/C
5	Cavity insulation	Loose fill rock wood cavity insulation
6	Sheathing	0.5" "Zipwall" sheathing
7	Vapour retarder	("Zipwall" acts as the vapour retarder)
8	Structural stud wall	2x6" stud wall at 24" O/C
9	Cavity insulation	Dense packed rock wool cavity insulation
10	Gypsum board	0.5" gypsum board

4.4.3.1 Larsen Truss Discussion

POSITIVE ATTRIBUTES:

A standoff wall can add significant insulation to an existing design. Its appeal is in its simplicity. In this assembly, a standard structural wall is built and sheathed as it would normally be. Then a layer of polyisocyanurate is applied to the exterior of the sheathing. This application is significantly easier than the standard practice of applying polyisocyanurate on the interior of the studs. It is easier because, when applying to the exterior, a single wide sheet can be wrapped around the house, minimizing seams. In standard practice, tying in the polyisocyanurate between the floors is often a significant challenge, as the floor joists get in the way and the polyisocyanurate is often either cut or put on the cold side of the insulation. There also are the seams in the polyisocyanurate which create the potential for air leakage if not properly sealed (Building Science Corporation, 2009). In a Larsen truss, though, the polyisocyanurate is attached under the sill plate and to the polyisocyanurate running over the ceiling. This is a significantly easier task. The polyisocyanurate in a Larsen truss assembly must have UV blockers, though, as there is potential that it will see significant sun exposure before it is covered by the trusses.

The truss is then attached to the structural wall through the poly and the sheathing as to increase the amount of insulation. A Larsen truss creates an uninterrupted cavity which limits thermal bridging because there is not a continuous connection between the chords of the truss. This cavity is generally filled with cellulose (Coldham, 2009). Holes are drilled in the exterior sheathing of the truss and cellulose is blown in to the truss bays. Many of the trusses used today are not site built, which eliminates multiple potential concerns, including the time associated with the on-site construction of the trusses, the building force’s learning curve for constructing the trusses, and the warping of trusses if they spend too much time exposed to the elements.

The trusses are generally run from the foundation to the bottom of the roof line, and because of this, the insulation is continuous, unlike in a double stud wall where the rim joists are potential thermal bridges. Windows are boxed in a similar method to the double stud wall, but unlike the double stud wall, the structure is separated from much of the insulation with a layer of sheathing and polyisocyanurate. This set-up addresses some of the concerns related to the tendency of a double stud wall to collect moisture. In a Larsen truss assembly, the studs are not in the same cavity as the exterior sheathing, which means that water vapour will not condense in the same cavity as the studs. However, a Larsen truss assembly can still have some of the “cold OSB” problems that a double stud wall may also have—but the consequences will not affect the structure.

BUILDABILITY:

A Larsen truss wall certainly has many characteristics which do not deviate significantly from standard practice. The structural wall is almost identical to a code built wall—minus the vapour retarder—which makes this portion of the wall construction more buildable (Canadian Home Builders' Association, 2008). There is also the relative ease with which the polyisocyanurate is applied, which results in fewer seams than other assemblies (Coldham, 2009). John Larsen, states regarding the differences between the wall assembly that bears his name and the double stud wall:

> *With a double-wall house, you still have a problem with sealing the* [air barrier]*. What we liked about my system was, you could frame the house normally. Let's say it's a two-story house with an outside wall that's 19 feet high. You could wrap the whole house with one piece of 20-foot wide polyethylene, and then put the trusses on top of that.*
>
> *Regular framers didn't get the concept of getting a house airtight. It was hard to re-train them sometimes. But with my system, you could get regular framers to frame the house, and we just came in later and put on the vapor barrier and the trusses* (Holladay, All About Larsen Tursses, 2011).

The beauty of the Larsen truss is in the simplicity of its premise: build a standard wall, wrap the house in polyisocyanurate, add the trusses and fill the standard wall and truss with insulation (Holladay, 2011). As well, the finishing of the house is very similar to standard practice. The drawing details will remain similar to best practices, and deep door and window bays are the only significant changes to the façade.

Because of the simplicity of its design, the Larsen truss is often used for retrofits. It is most appropriate for the application because homeowners wanting to significantly increase the insulation of their wall can have their existing façade dismantled, a layer of polyisocyanurate applied, and the trusses attached and filled. This raises concerns related to the creation of a 'vapour trap' if there is already a layer of polyisocyanurate on the interior of the structural studs. To address this issue, the interior gypsum board has to be removed to access the interior polyisocyanurate. However, condensation within the interior wall is unlikely, as the sheathing sandwiched between the structural wall and the truss would remain warm in winter.

PROBLEMS WITH BUILDABILITY:

Though a Larsen truss wall assembly does have some buildable attributes such as the structural wall and the placement of the vapour retarder, the truss portion of the assembly is where it loses favour regarding buildability. Adding a truss to the exterior of a traditional wall assembly is a significant deviation from standard practice. The trusses are long and cumbersome, and the work would require at the bare minimum scaffolding and ideally a crane. There are also concerns related to the storage of the trusses on site. As they are generally made out of 2x2s with a plywood spacer, if left out in the elements the trusses can warp due to moisture or sun exposure (Holladay, All About Larsen Tursses, 2011).

If the trusses are to be site-built—as a significant number still are (Coldham, 2009), especially outside of western Canada (Nesson & Dutt, 1985)—this is another significant deviation from standard practice, and is devastating to buildability. None of the trades would have experience building these kinds of trusses. The framers would be the closest to a trade that could deal with this; however, truss-building is not what they normally do, and it therefore comes at a cost. That cost includes education, labour, time and performance.

> *"Neither my general contractor, nor my builder had ever heard of a Larsen truss," said Topher Belknap, a green consultant who built a Larsen truss house in Edgecomb, Maine. "I had to educate them, and we had many discussions about various details. This required not only knowledge on my part, but also a firm belief that this is what I wanted. It also required paying for someone else's learning"* (Holladay, All About Larsen Tursses, 2011).

The quality of the workmanship is a major factor affecting the buildability of a truss assembly. If the trusses are site-built there can be significant problems related to the exterior finish of the building (Leonard, 2014). Because the trades are not used to or trained this task, they have little perspective on what will and what won't work. Their precision in making site-built trusses has no point of reference.

Moreover, installation is also a significant factor related to buildability. Outside corners in this instance have been identified as a significant detriment to this assembly's buildability, as builders find them "difficult to execute" (Holladay, All About Larsen Tursses, 2011). If batt insulation is applied within the trusses, problems related to installation can occur as well: "Gaps may occur in the insulation if the trusses are not correctly spaced and insulation is not properly installed" (Canadian Home Builders' Association, 2008). Because batt insulation can only be installed relative to its width, if the trusses are not spaced precisely, the batts will leave small air gaps; these kinds of gaps allow for air movement, which is a significant factor in the "cold OSB" problem.

Dense packed cellulose is often used to fill the trusses, but it has its own problems even though it addresses the issues related to batt insulation and the precision of the truss spacing. Cellulose installation inside the trusses can be difficult. In terms of blown in cellulose, installers are often inexperienced in filling such a large cavity and in judging the density of the required cellulose. This can result in settling and gaps in the insulation inside the trusses. Holladay quotes Belknap: "The problems I had with the insulation were attributable to the fact that the cellulose would drift from one bay to the next, and some of the bays would never get filled" (Holladay, All About Larsen Tursses, 2011). To address the issue of drift, some builders are baffling the truss compartments, which adds yet another task to the project. Another solution is to do away with the site-built trusses altogether and use vertical I-beams instead. This decreases labour and addresses the issue of drift between the truss cavities. Again according to Belknap: "The trusses did represent a substantial chunk of labor (on site) and may have caused some problems with the insulation. I-beams are now commonplace" (Holladay, All About Larsen Tursses, 2011).

By removing the site-built component from the equation, the buildability of a Larsen truss assembly does increase; however, it is still a significant deviation from standard practice.

CONSTRUCTION METHOD:

A traditional wall is built. A layer of poly is wrapped around the house so that it is continuous. The truss is then through the poly and sheathing and into the structure. The trusses are closed in using sheathing and insulation is blown in through holes created in the exterior. The traditional wall cavity is also filled with insulation. Windows have the same window bucks which are used in the double stud wall assemblies. The home is then clad using methods similar to common practice.

CONCLUSION:

The Larsen truss wall assembly is an effective method of superinsulating a home. It encloses the interior of the home quickly in a method that reflects standard practice. It has improved the application of the vapour retarder, eliminating the majority of seams and limiting the number of penetrations by use of the structural wall as a chase. However, it does fall in to the same "cold OSB" trap as the double stud wall. Because of these concerns, air tightness and proper detailing of the assembly is essential to the assembly's success.

In terms of the trusses, if they are site built, this has a major negative effect on the buildability of this assembly. Even if the trusses are prefabricated, their application to the structural wall is unrelated to conventional expertise. The installation of insulation is difficult and has the potential to effect the performance and durability of the truss assembly.

4.3.4 Vertical TJI Wall – Fort St. John

Of all of the assemblies assessed this MRP, the vertical TJI assembly is the hardest to define. There are two specific features which identify this assembly and plenty of variations in its application. The two features are (1) the use of a wooden truss joists (TJIs) in a vertical position for the creations of a cavity that is filled with insulation, and (2) the use of a vapour open sheathing to the exterior of the TJIs. The variation in the applications of TJIs is as follows: TJIs are sometimes used as the structural element of a building, with our without an interior chase wall, and TJIs are sometimes applied to the exterior of a standard practice wall in an application which resembles a Larsen truss assembly. For clarity, the TJI assembly referred to in this MRP is as the structural component of an assembly.

The system of using vertical TJIs came from Europe. The first Passive House single-family dwelling in North America used this assembly and was designed by Katrin Klingenberg, one of PHIUS's founders (Holladay, 2013). Klingenberg uses TJIs structurally without an interior 2x4 chase wall, though the use of a chase has become popular in the application of this assembly.

The Fort St. John home is a Passive House design from British Columbia, built in 2013. The superinsulated wall is constructed as structural vertical TJIs with an interior chase wall.

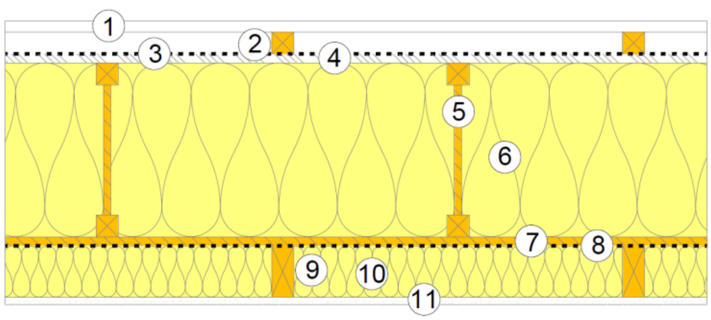


Figure 9: Wall section detail of the Fort St. John home in plan view (vertical TJIs).

	Elements of a Vertical TJI Assembly	Fort St. John
1	Exterior finish	0.75" cedar shingles or metal siding
2	Strapping	1.5" treated battens
3	Weather barrier system	Building paper
4	Sheathing	0.625" Agepan diffusion board
5	Vertical TJIs	11.875" TJIs @ 24" O/C
6	Cavity insulation	Roxul
7	Sheathing	0.625" OSB

8	Vapour retarder	(OSB acts as the vapour retarder)
9	Structural stud wall	2x4" stud wall
10	Cavity insulation	Roxul

4.3.4.1 Vertical TJI Discussion

POSITIVE ATTRIBUTES:

The innovative component of this assembly is its use of vapour permeable sheathing on the exterior of the TJIs. By replacing the OSB—which would be the most common exterior sheathing—with something dramatically more permeable, designers can improve the opportunity for the insulation cavity to dry.

> *The key to the success of this construction is the sheathing on the outside of the TJIs. This sheathing is a high-perm fiberboard which allows a full 2/3rds of the wall to dry towards the outside* (Holladay, The Klingenberg Wall, 2013).

OSB at 2 perms is considered vapour semi-permeable, while plywood at 10 perms is closer to vapour permeable (Building Science Corperation, 2010). This means that, by switching from OSB to high-perm fiberboard, the permeance of the material is increased ten times; from plywood, the permeance is doubled, increasing the drying potential of the assembly (Green Building Advisor, 2010).

As with the previous example, air sealing is essential to the success of this assembly. The risks associated with water vapour collecting inside the wall cavity are similar to those in a double stud wall assembly. In the double stud wall assembly, the risk of collecting water vapour within the cavity is that the presence of water could allow for the growth of mold and rot which, in the case of rot, would compromise the structure. The same is true of a vertical TJI assembly, as the structure is in the same cavity as the cold exterior sheathing. Straube notes of the fiberboard, "Technically speaking, there remain risks of exterior sheathing wetting because of the cold-side sheathing. But using vapor-permeable sheathing goes a long way to mitigating the risks" (Holladay, The Klingenberg Wall, 2013). Straube is not saying that, by using fiberboard sheathing, all the problems related to cold exterior sheathing are solved. As with the double stud wall, a vertical TJI assembly is still quite difficult to air seal, and if water vapour makes it through the assembly to the cold fiberboard, condensation is likely to happen. What Straube is saying, however, is that the potential for drying in such a situation is increased by the use of a highly permeable material.

BUILDABILITY:

As would be expected, this assembly deviates significantly from standard practice. There are many variations on how this assembly is constructed, and therefore the location and the detail drawings have to play a significant role in the assessment of this assembly. Framers are familiar with TJIs for framing floors; however, this does not mean that they would be familiar with their use in walls, and certainly not as a building's vertical structure. To compound the deviation, TJIs in North America are not designed to be used vertically or to carry a compressive load (Holladay, The Klingenberg Wall, 2013). All of this sets vertical TJIs as structure quite far apart from what would be considered standard practice. TJI walls also require a crane to lift them, decreasing the buildability by adding machinery.

PROBLEMS WITH BUILDABILITY:

As was suggested in the previous section, vertical TJIs are a "hard sell" when it comes to buildability. They vary significantly from standard practice, use materials which are uncommon and may not be available locally, and they require a crane to set them in place once built. On top of all of that, they are expensive and labour-intensive to work with.

Here are some of the problems Straube sees with vertical TJIs:

> *How do I attach the I-joists to the sill plate? How do I attach cladding and sheathing? And to what end? It's easier to build a double-stud wall than an I-joist wall. I have no answer as to why. An I-joist wall has no performance benefits over a double-stud wall, and no price benefit* (Holladay, The Klingenberg Wall, 2013).

With questionable benefits and the added cost, vertical TJIs are a hard sell over the double stud wall; however, Straube may be playing down the positive attributes of fiberboard (notably its permeability).

Though a highly permeable sheathing is an innovative prospect, the fiberboard is not a perfect substitute for either OSB or plywood in terms of buildability. The positives of drying outward may be outweighed by the negatives related to the buildability of this material. According to Chris Corson:

> *"On some projects we've used high-perm fiberboard for exterior sheathing… It worked; it did its job. But it's difficult to work with. It's hard to install. It's dirty. It smells like asphalt. When we started installing the cellulose insulation, it really bellied out. Fortunately we caught the bellying before it became a big problem. We finished the job by watching it closely and babysitting the insulation contractor"* (Holladay, The Klingenberg Wall, 2013).

Fiberboard may increase the drying potential for this assembly, but in terms of buildability, the vertical TJIs as structure is less than ideal, and the fiberboard can be a hassle to work with.

CONSTRUCTION METHOD:

For applications where a vertical TJI component of a wall assembly is structural, balloon framing is common. If built on site, walls are constructed on the deck and lifted into place using a crane. In the example from the Fort St. John house, OSB sheathing was applied to the interior of the TJIs, followed by a vapour retarder and the interior chase wall. To the exterior, the fiberboard sheathing was applied and the cavity filled with insulation. This was followed by house wrap as part of an air barrier system. The façade was then applied to the exterior and, once the trades have done their thing in the chase wall, the stud cavity was insulated and the interior was drywalled.

CONCLUSION:

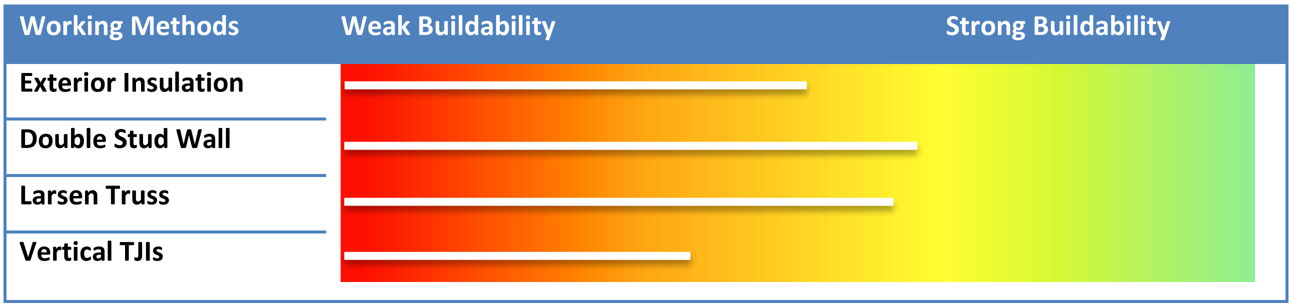
Vertical TJIs have found a place in PH. Their use continues in North America, and though it is not a hugely popular building method in Europe, there is a Swedish company producing TJIs designed to be placed vertically and take a compressive force (Holladay, The Klingenberg Wall, 2013). The success of this assembly may have to do with the importance of its history here in North America or the designer whose name has been adopted for this method (Klingenberg), but it is doubtful its success is as a result of its buildability. The deviation from standard practice is significant; it is expensive; it uses components for a purpose they are not intended; ultimately and most importantly for this project, it seems it is less than ideal when it comes to its working methods.

4.5 The Tool

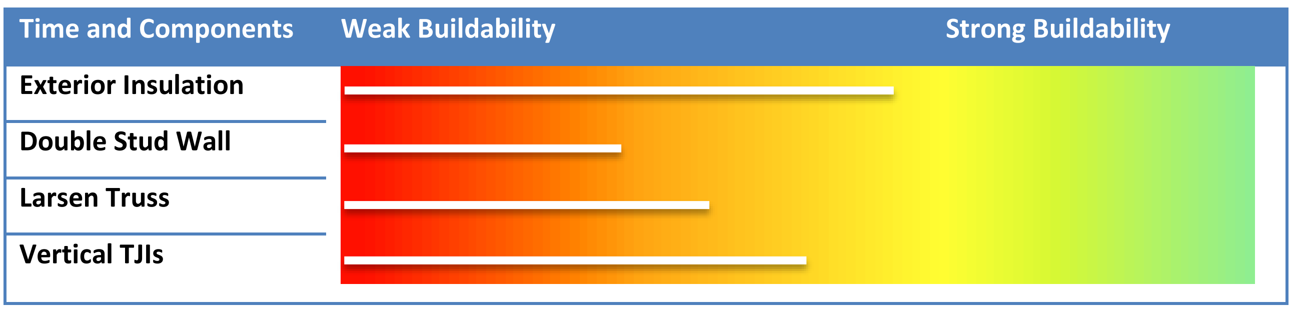
The tool that is included in Appendix I was drafted in June 2014; this is the version of the tool that was reviewed by industry professionals in early July 2014. It was used to evaluate the four case study wall assemblies—the Jackman Residence, the Tree Eco-Village, the Pedlar Residence, and the Fort St. John house—each corresponding to four types of superinsulated assemblies—exterior insulation, double stud wall, Larsen truss, and vertical TJIs, respectively. Users of this tool will be able to analyze the ease or difficulty of their specific project, and should then be able to modify or prepare for impediments to the success of their build.

CHAPTER 5: RESULTS

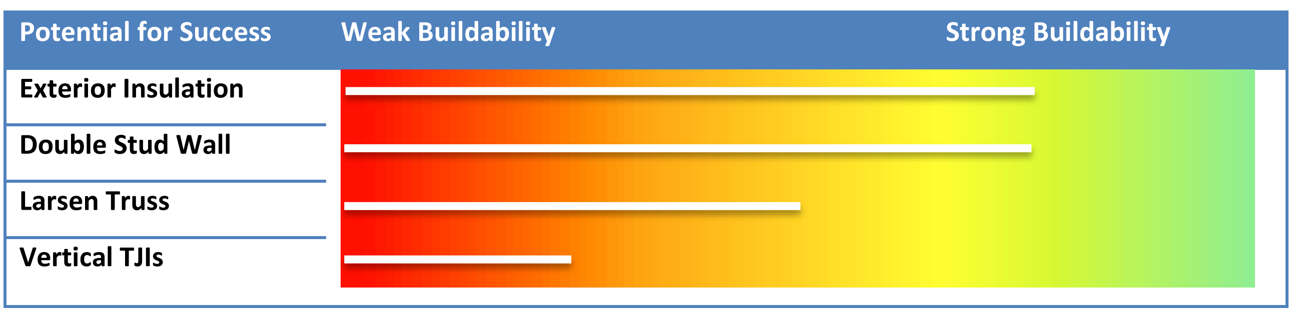
Each of the four assemblies were assessed using the tool in Appendix I. The following table was used to graph the results from the tool visually, for the purpose of *comparison*. For both sets of graphs, the longer the horizontal line, the stronger relationship with buildability. For the each of four assemblies, neither Trades nor Materials are assessed in this MRP as both are highly dependent on the local context.



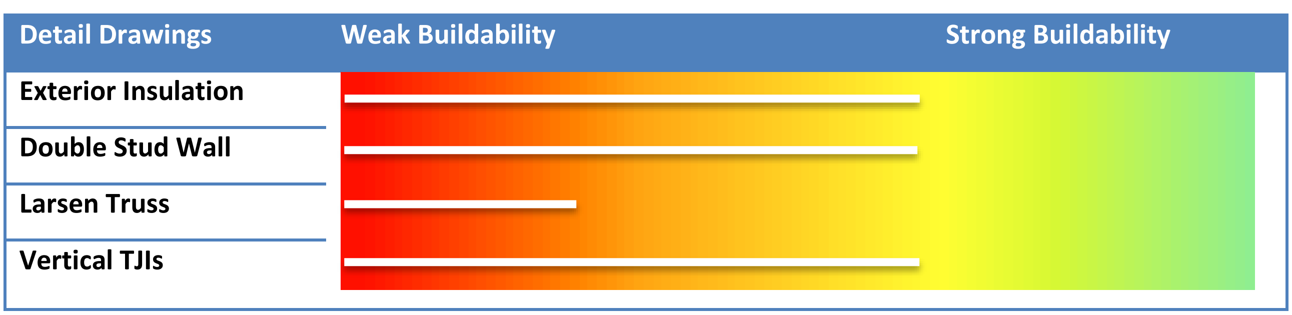
Graph 1: Working Methods Metric



Graph 2: Time and Components Metric



Graph 3: Potential for Success Metric



Graph 4: Detail Drawings Metric

5.1 Results for Superinsulated Assemblies

Each of the four identified assemblies were assessed to qualify their buildability using the proposed model. The following four sections provide the break-down of how the results shown on the graphs on p. 53 were reached.

5.1.1 Jackman Residence—Exterior Insulation (see Appendix II)

Results from the analysis of the case study for an exterior insulation assembly, the Jackman Residence (see Appendix II for the completed question sheet for this assembly).

Metric	Working Methods	Time and Components	Potential for Success	Detail Drawings	Trades	Materials
Score	8/12	11/15	10/12	9/12	N/A	N/A

The Jackman Residence was one of the strongest assemblies in terms of buildability as assessed by this tool. None of the results from the four metrics used for judging this assembly crossed over into the "Weak Buildability" section of the table. Working Methods was the assemblies weakest metric in terms of buildability, and yet it reached just above the centre of the table, meaning that its working methods were *less* buildable, but not *difficult to build* (see Graph 1). The Jackman Residence's wall assembly's buildability was weakened because its fasteners deviate significantly from standard practice: they are long screws that must be screwed through the strapping, through the exterior insulation and finally into the structure.

> *This is a relatively new method of cladding attachment, driven by exterior-insulated assemblies. Therefore, the design communities do not necessarily have a good understanding of it yet, and there may still be hesitation about using this strategy* (F.P. Innovations, 2013).

It is obvious that the application of insulation on the exterior of the assembly is significantly more complex in working method than is standard practice. The techniques are new which meant that—as stated above—designers are not particularly comfortable with the assembly. Also, as this attachment method is so new, the trades would not be as familiar with the method as they may be with a more traditional approach.

In terms of the Working Methods metric, the Jackman assembly scored well in its use of lumber. The use of a standard practice wall certainly improves the working method of this assembly and therefore its buildability.

One particularly strong point for the Jackman Residence assembly was its potential for success, which received a highly buildable score. Its only downfall in this metric was its requirements for additional detail drawings. While many assemblies have a layer of sheathing to the exterior, an exterior insulation assembly simply has the rigid insulation, whether it be rigid batt or in this case 6” of foil faced polyisocyanurate. The exterior insulation makes corners or penetration details such as windows or doors more complicated, as they cannot be flush mounted in the same method as would be standard practice. Special details must be drawn up to address these intersections in the assembly.

The additional detail drawings aside, placing insulation to the exterior of the structure and eliminating sheathing exposure to exterior temperatures does great things for an assembly. It allows the assembly to stay dry, and to dry itself if it does gets wet, which in turn improve the assembly’s durability. In the Jackman assembly, as in most exterior insulation assemblies, the air barrier system is protected and supported as it is adhered to the sheathing on the exterior of the structural wall and protected by the exterior rigid insulation.

In the case of the Jackman Residence, the assembly has a rain screen as its exterior layer. A rainscreen prevents sun-driven moisture and allows the assembly to dry to the exterior. The drainage layer in this particular assembly is the foil facing adhered to the polyisocyanurate (ISO). This facing is considered a vapour retarder; because the seams are staggered, foamed and taped, the drying potential of the ISO towards the exterior is low. Though a vapour retarder to the exterior of the insulation is unconventional, ISO is a moisture-resistant foam (Polyiso, 2014) and therefore any small amounts of moisture which make it into the ISO is unlikely to cause damage to the assembly.

The Jackman assembly has tremendous potential to dry to the interior as there is not a traditional vapour retarder on the warm side of the insulation. Instead, the cavity filled with dense-pack cellulose insulation is able to dry through the wall towards the interior.

Overall the Jackman Residence’s wall assembly was judged by the assessment tool to be highly buildable. Along with the many other positive benefits, exterior insulation is a highly successful assembly which requires a minimal deviation from standard practice, and as judged by this tool, is one of the better choices for a superinsulated assembly.

5.1.2 Tree Eco-Village—Double Stud Wall (see Appendix III)

Results from the analysis of the case study for a double stud wall assembly, the Tree Eco-Village (see Appendix III for the completed question sheet for this assembly).

Metric	Working Methods	Time and Components	Potential for Success	Detail Drawings	Trades	Materials
Score	9/12	8/15	10/12	9/12	N/A	N/A

The Eco-Village Tree assembly had a strong showing in the Working Methods. Though a double stud wall assembly does require the construction of two walls, both walls are very close to standard practice and therefore an assembly using this method of construction should have done well in Working Methods. Unlike the other three assemblies, the work of framing and creating the assembly for this method is directly related to the construction methods used by tradespeople every day.

As would be expected, Time and Components saw a significant increase. When constructing a double stud wall, the amount of wood, insulation and time all increase, making the wall less buildable (Aldrich, Arena, & Zoeller, 2010). This increase might be offset in the Materials metric. The materials in this assembly are identical to standard practice and they are used in a very similar manner. As well, though two walls are constructed using the double stud method, the amount of lumber used in the structure is not necessarily doubled.

In the Tree Eco-Village building, both the exterior and the interior of the double stud wall used standard 16” o/c framing. This was a missed opportunity to use advanced framing, but not for the most obvious reasons. Advanced framing is often used to decrease thermal bridging. Instead of 16” o/c, studs are placed at 24” o/c with a single top plate and with the floor joists lined up directly above the wall studs. By limiting the amount of studs in the exterior of the wall, the amount of thermal bridging is decreased. In a double wall assembly, however, there is already a thermal break between the studs; thermal bridging thus has already been addressed in this assembly.

Though Time and Components were not particularly strong in the Tree Eco-Village, some planning between the framers and the designer, as well as the use of advanced framing, may have saved some time and materials.

The Potential for Success of this assembly was quite strong; it had the same buildability buildable as the exterior insulation assembly. As was identified in the literature, walls without exterior sheathing have the potential for hydrothermal performance problems as related to air leaks, condensation and drying potential. In a double stud wall assembly in particular, there is no interior barrier between the structural wall and the cold sheathing. If condensation were to result or a leak in the exterior were to occur, that moisture would collect in the cavity exactly where the structure of that assembly occurs. This situation is less than ideal for the durability of the structure or the health of the people inside. Meticulous attention to the interior vapour retarder and the exterior air barrier/weather control layer are vital to the durability and ultimately the success of this assembly. All of this makes the results seem strange. The tool did a poor job of identifying the weaknesses of a double stud wall in terms of its potential for success.

Another area where the Tree Eco-Village assembly varied significantly from standard practice was in its usage of rigid insulation inside the stud cavity. Though EPS foam performs better hydrothermally than cellulose insulation (a common insulation in a double stud wall), the labour required to fit the foam sheets between the studs and into corners (see Figure 13) in the Tree Eco-Village would have been significantly greater than in standard practice. As well, the continuity of the insulation could be called into question in such an application. In a double stud wall, it would be difficult to assess if the insulation was truly continuous in the cavity as EPS is not known for its durability; a visual assessment of the application would be limited to what was in plain sight, which is generally an inadequate form of assessment. Spaces and gaps between the insulation could allow for air movement within the cavity, which is exactly what the insulation is there to prevent. As well, because of this assembly's aforementioned weakness related to moisture accumulation, the consequences of using EPS in this cavity—in terms of air movement—could have a significant negative impact on durability. A thermal imaging camera would be a huge asset in identifying weaknesses in the insulation installation.

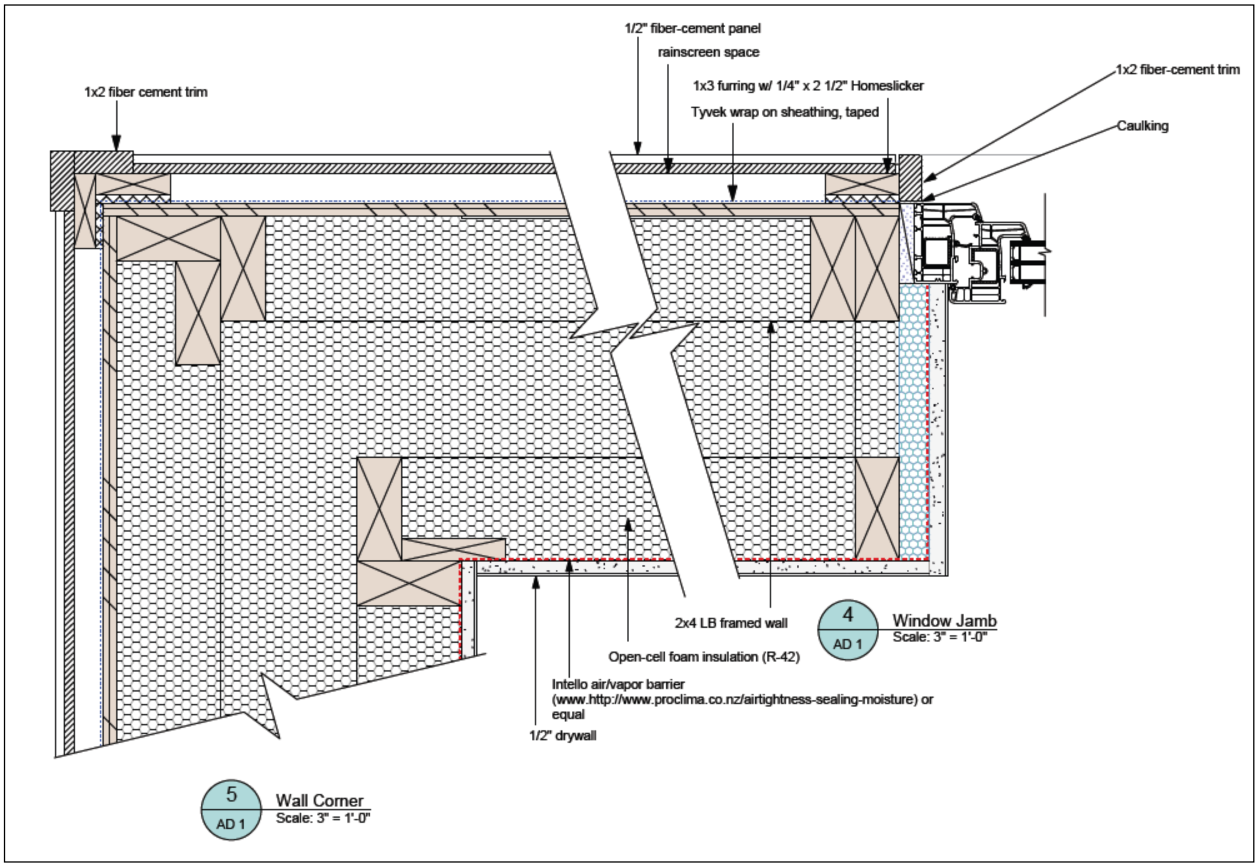


Figure 10: Exterior Corner Detail from the Tree Eco-Village building (Coterre Planning Development Design, 2012).

The double stud wall assembly a highly buildable in terms of Working Methods, as this assembly relates directly to standard practice is most aspects. However, it is a wall assembly which has its flaws, and the tool was successful in identifying and highlighting some of these flaws, but not all of them. If this assembly were to be chosen for a project, then the tool should make the designer, project manager and tradespeople aware of these deficiencies. This awareness would allow for problem solving and an emphasis on ensuring the quality of the assembly's potential weak spots. The Potential for Success metric therefore needs some refinement.

5.1.3 Pedler Residence—Larsen Truss (see Appendix IV)

Results from the analysis of the case study for a Larsen Truss assembly, the Pedler Residence (see Appendix III for the completed question sheet for this assembly).

Metric	Working Methods	Time and Components	Potential for Success	Detail Drawings	Trades	Materials
Score	11/15	9/15	8/12	6/12	N/A	N/A

Overall, the Pedler Residence's assembly received one of the lowest scores out of the four assemblies; that is, it is one of the least buildable of the four examples. Though its Working Methods were significantly more buildable than those of the Fort St. John assembly, the Pedler Residence was a poor performer. The Working Methods were reasonably good, as the structural wall in this assembly reflects standard practice and the vapour retarder is easier to apply than even standard practice.

The weakest aspect of the Pedler Residence in terms of buildability was in its Detail Drawings. Unfortunately there were only five details for the entire house. The details identified the major connections, but left out major aspects of the construction, including an exterior corner. A corner in a Larsen Truss assembly was identified in literature as one of the most difficult aspects of this assembly to execute (Holladay, 2011). Without a detail explaining how the corners were to be constructed, the decisions in that regard are left up to the construction manager or the trades. Because this assembly is not common, it is unreasonable to leave the complexity of such a detail to a site decision. On-site problem solving such as this has the potential to severely compromise the performance and durability of this assembly. The tool did a sufficient job of identifying this deficiency in the drawings and relaying that information in the graph.

The Potential for Success in the Larsen Truss assembly did better than the Detail Drawings metric. This success, though mild, is directly related to two aspects of this assembly. They are: the exterior sheathing, which ensures the façade details are reasonably similar to best practices, and the vapour permeability of the materials used. The Pedler Residence assembly can dry in both directions. This is because there is no Class I vapour retarder, which means that water vapour can travel through the entire assembly. There is, however, one Class II vapour retarder in the assembly: the Zip System plywood. The vapour retarder is positioned on the warm side of the majority of the insulation, which is appropriate, and as with most barriers in this section of a Larsen Truss assembly, has limited penetrations. This arrangement meant that the stud cavity insulation has great drying potential to the interior, which will protect the structure from damage due to moisture.

The outwards drying is from the Zip System through the loose fill rock wool cavity insulation, a sheet of ½" plywood and the air barrier. Plywood has a higher permeance than OSB so it is a good choice here, and the Tyvek layer also has a high permeance, which promotes drying through this layer. The unfortunate aspect of the Pedler Residence is the lack of a rain screen.

The Pedler Residence is clad with wood shingle siding. These shingles are sure to absorb moisture in wet weather, but without a drainage layer behind the shingles, this could result in a moisture problems related to sun-driven moisture in the assembly. As in the double stud wall, a Larsen Truss assembly has potential problems due to air sealing, moisture management and cold exterior sheathing. Add to that sun-driven moisture, and the durability of this assembly is likely to suffer.

The buildability tool suggested that the Pedler Residence is one of the weaker assemblies assessed. Its strongest results were in Working Methods because of its standard practice wall and the vapour retarder/air barrier installation. The weakest metric as related to this assembly was in the Detail Drawings, which were not descriptive and were too few, not clearly identifying and describing one of the most difficult details of this assembly, the exterior corner. This assembly did have some positive attributes including the prefabricated trusses and the inwards drying, but overall this assembly would be considered less buildable, heading towards weak buildability.

5.1.4 Fort St. John—Vertical TJI (see Appendix V)

Results from the analysis of the case study for a vertical TJI assembly, Fort St. John (see Appendix IV for the completed question sheet for this assembly).

Metric	Working Methods	Time and Components	Potential for Success	Detail Drawings	Trades	Materials
Score	7/12	12/18	6/12	9/12	n/a	n/a

There are many methods which include TJIs in superinsulated assemblies. The method used in the Fort St. John house had the TJIs acting as the structure, with an interior 2x4” chase wall. Using TJIs as structure deviates significantly from standard practice. Using TJIs in such a way is an uncommon use of materials. Tradespeople implementing such an assembly would take a lot of time to learn the assembly, become comfortable with its implementation, and become efficient in its production. Robert Blancett identified these three stages in his paper “Learning from Productivity and Learning Curves.” According to Blancett, the first phase can take up to 6 months with flat productivity, followed by an efficiency phase where productivity increases, and finally by a mature phase where the gains in productivity are won. Going through these three phases takes a significant amount of time—more time than is realistic for a North American building site. Therefore, the assembly’s buildability would suffer as related to Working Methods.

By contrast, the Fort St. John assembly does reasonably well in two of the metrics, peaking with Detail Drawings. This was the only assembly tested which included a penetrations detail. As well, all of the assembly’s intersections—at the walls, at the floors and at the slab—had their own separate detail drawings, which described the specific materials and highlighted the assembly’s barriers. The drawings for this building are impeccable, the design is simple, and the explanations are thorough. A Therm image is included for the foundation to highlight the continuity of the insulation and the components of the assembly. All of these combine to give the Fort St. John assembly a low (highly buildable) score for Detail Drawings.

The Potential for Success received a very low score. The weakness of this assembly was due to two significant factors: the susceptibility to deficiencies; the issue of code compliance; and the characteristics of the exterior finish—a diffusion board sheathing—which, although related to standard practice, is harder to work with than plywood or OSBs.

Understandably, Time and Components had a weaker showing in this assembly because the amount of material (such as insulation and sheathing) increased. Although the Materials metric was not judged because the specifics of the local context couldn't be determined, it is likely that this assembly would have done poorly in the Materials metric; the defining feature of a TJI assembly is the exterior sheathing, which is highly permeable but not in common use. Some complaints in terms of the machining and application of this "diffusion board" (as they called it in the Fort St. John plans) were also identified in the literature review.

As mentioned previously, TJI assembles come in many forms. The Fort St. John house, though not ideal, showed some real success related to buildability, especially in the quality of the drawings and the assembly's drying potential.

CHAPTER 6: DISCUSSION

6.1 The Model as Assessed by Industry Experts

The model was sent out without the assessments to six industry experts, three of whom are designer/builders and three of whom work in building science as consultants. Each expert was sent a six-page document (see Appendix I), which included an introduction to the model's use, the model question sheet itself, and a series of instructions or examples related to how the questions should be scored. The industry experts were asked to comment on the tool by responding to the six questions which accompanied it. Three of the industry experts responded, two working as building science consultants and one working as a designer/builder. Their responses are grouped below to reflect the metrics to which they are referring. Their suggestions are also incorporated into an "Evaluation Sheet and Revised User Guide" which can be found in Appendix VI.

6.1.1 Working Methods Assessment

The experts identified a few aspects related to Working Methods which were not addressed with the existing questions. Cohen was concerned with the scoring of Question 1.2 (see Appendix I) as it related to Prefabrication. "I do not agree with this metric as, depending on the situation, site built could actually be more efficient" (Cohen, 2014). Cohen is right: there certainly are situations in which something built on site would be more buildable than something prefabricated. Cohen's business is prefabricating wall assembles for superinsulated walls, so he should know. However, in the Question Sheet, the instructions for Question 1.2 state that the question is "Larsen Truss specific." For assemblies which do not include a Larsen Truss, a simple N/A will suffice. However the nature of a Larsen Truss is its deviation from standard practice. These trusses were traditionally constructed from 2x4s cut into 2x2s and screwed to plywood gussets; the trusses are then spaced 24" apart. This construction is common practice to none of the tradespeople on site. Assigning a framing crew to construct a multitude of these trusses on site would be a lesson in patience at best and futility at worst. It is reasonable to have stated that, if a Larsen Truss is prefabricated, then the truss has a stronger relationship to buildability than a) a truss built on site, by trades who have no experience in this form of construction or b) a truss that must be "cut to length," as was stated in the Question Sheet. A Larsen Truss specific question, however, is less than ideal. Ideally, every question in the tool should be able to assess any detail. By including a question specifically targeted at an assembly, the tool becomes less versatile. What if a new method of wood framed assembly where to be developed? If the tool included questions which were too specific, a new method would require new questions and thus new revisions to the tool. The fabrication of a wall truss system on site would certainly be less buildable, but there needs to be a more general question for addressing this weakness in the Larsen truss assembly.

Both Cohen and Trainor had slight adjustments to make to the assessment of the Insulation Installation in Question 1.5 of the Question Sheet. Trainor identified that spray foam, which was assessed as a 3, should be demoted "since it requires special equipment, specially trained operators and is somewhat weather dependent. Anything over 2 inches must be applied in layers with setting time between each layer" (Trainor, 2014). Spray foam, which requires a single application, was therefore demoted to a moderate relationship with buildability in the Revised User Guide, and spray foam requiring more than one application was demoted to a weak relationship with buildability. As well, in terms of dense packed cellulose, Cohen stated, "Dense pack cellulose is standard practice in many areas and has no upcharge in time or cost" (2014). This was helpful feedback because dense pack cellulose in a deep cavity as well as dense pack cellulose in a baffled cavity had been identified in the Question Sheet, but cellulose in a cavity up to 6" deep had not. The Revised User Guide was updated adding cellulose to the small cavity option.

6.1.2 Time and Components Assessment

Cohen was concerned with the comparison between standard practice and superinsulated walls. He found it inappropriate to compare an R-13 wall to an R-50 wall, as the R-50 wall is obviously a more robust assembly (2014). Though it is true that defining buildability as "an assembly which takes longer to construct or requires more components" immediately identifies superinsulated walls as less buildable, this is not an unreasonable statement. If the definition of buildability is "the ease with which a project can be built," then a building which requires more time and materials is less buildable. However, the strength of this model is not in its ability to assess an assembly to a universal standard; rather, the strength of this model is that it looks at a specific assembly in its local context and can assess that assembly against other assemblies in the same context. Though the model is judging buildability, this MRP is not suggesting that R-50 walls be replaced with R-13 walls, even though the R-13 wall is more buildable; rather, the objective of this model is to help designers and builders known how easy or difficult it will be for a local crew to construct different R-50 assemblies. The purpose of the model is to assess the differences between two potential assemblies in the same context.

Graham Finch identified weight and wall thickness as two aspects which could be added to the Time and Components metric on the Question Sheet; the Revised User Guide contains these additions.

6.1.3 Potential for Success

This section of the tool was less than accurate. Though the tool did an appropriate job identifying the weaknesses in the Larsen Truss and the Vertical TJI assembly, the tool did not identify the weakness associated with the Double stud assembly. Double stud walls are known for moisture problems and the structural wall in the case of the Tree Eco-Village house was in the same cavity as the exterior sheathing. This metric obviously needs to stress the importance of moisture management. The experts agreed that there were a few essential questions missing for the Potential for Success metric. Trainor (2014) suggested that, instead of "susceptibility to deficiencies," "wetting potential" and "drying potential" would be more directed towards the assembly's true potential. He stated:

> *Cold OSB is one factor in wetting potential as is the complexity (buildability) of the water control features such as flashings and the complexity in maintaining continuity of the air barrier. Drying potential will include vapour permeability of materials exterior to and interior to the sheathing as well as ventilation of the cladding system* (Trainor, 2014).

Graham Finch (2014) believed that "durability" would also be a good addition to this metric. Cohen (2014) stated, "In superinsulated assemblies, commissioning of the envelope is critical for success, [and] both air testing and thermal imaging are required. There should be some acknowledgement and discussion of this I think." To identify the importance of envelope commissioning, a new Question 3.7—related to thermal imaging and a blower door test—was added to the Revised Use Guide (see Appendix VI).

This model is not objective; rather, the Revised User Guide enables a subjective assessment of buildability. For example, Question 3.5 in the Revised User Guide requires a user to rate how "reliable, supported, redundant and effective" the connections are; one user may determine that one assembly's connections are reliable while another user may say that they aren't. This tool will work best if the same person always assesses each assembly.

6.1.4 Detail Drawings Assessment

Firstly, Trainor suggested that the metric should be called "Detail Drawings" instead of simply "Details" to eliminate any confusion related to what this metric is actually assessing. Finch (2014) suggested that, though a 8'x8' section of wall was less help in terms of buildability, it may be more effective to judge some general assembly details for each assembly put forward (including an inside corner, and outside corner and a window). In Straube's work on superinsulated walls, he looked at a wall section separately from the detail drawings. Finch is correct that judging some specific details regarding corners and penetrations is essential to assessing buildability; however, the wall section still has its value. By assessing the wall assembly without windows or corners, the clarity of the assembly alone is increased. Though details such as windows and corners are a significant part of how the walls go together, it is also important to understand the nature of the construction itself, and this is laid bare when dealing with an unembellished 8’x8’ wall section. The Revised User Guide contains a note that suggests that it is advisable to run the Detail Drawings metric on the three details identified by Finch.

Cohen identified the Detail Drawings metric as greater than simply the clarity of the drawings. “Here simplicity, repeatability and the ability to trouble shoot are critical, not just the clearness of the detail drawn. Many clearly drawn details are hard to implement” (Cohen, 2014). To improve the accuracy of this metric, it was essential to identify the aspect of the detail drawings which Cohen identified. To implement this Question 4.3 was changed in the Revised User Guide to reflect the simplicity of the implementation of the details and the repetition inherent in the details. By refining this question, the metric not only looks at the clarity and quality of the drawings, but also at the ease of assembly that the drawings portray.

6.1.5 Trades Assessment

Cohen identified that the performance of the tradespeople was not being assessed successfully in this metric:

> *Here I think you must acknowledge that if the details are simple and straight forward the real metric should be “How many iterations will it take for tradesman to get up to speed?” Assume the tradespeople are starting at zero, the real issue is can they become adept and efficient in one project, two, three? Our prefab wall system is based on intuitive understanding for the average carpenter, so they can have success [on] day one* (Cohen, 2014).

In the Vertical TJIs section (6.1.4 of this MRP—see page 61), the performance of the tradespeople as it related to learning was addressed. Assessing how long it would take for a tradesperson to get “up to speed” would be too difficult to judge as each tradesperson on site would have to be interviewed. In his paper, Blancett (2002) talks in terms of months and years to get to a point where a process can be refined for efficiency. Cohen is talking about days, and “days” is a more appropriate timeframe for construction. Amerongen (2014) stated that his framing crew gets a bit of on-site training regarding advanced framing, and then they are sent to work under close supervision by a construction manager.

The Revised User Guide does bring some clarity in response to Cohen's feedback. Experience and education are two questions which are addressed thoroughly in the Revised User Guide, assessing the number of jobs with this assembly that the tradespeople have worked on, as well as the tradespeople's understanding of advanced envelopes. The assessment will identify if the trades have knowledge and experience. As to how many interactions the tradespeople must go through to be "up to speed," it must be assumed that, the more experience they have with the assembly, the more up to speed they are.

Finch (2014) identified sequencing as one of the features related to the trades which was absent in the Question Sheet. "If you have the same trade coming back to site on multiple times due to sequencing that will affect buildability. Therefore you may need to provide the build steps for each assembly and assign different trade to each" (Finch, 2014). To address the importance of sequencing on site, Question 5.5 was added to the Trades metric in the Revised User Guide. It relates buildability to planning the sequencing of events on site, and identifying which trades work continuously and which must be called back onto the site.

6.1.6 Materials Assessment

Only one suggestion was provided for this metric and it is used in the Revised User Guide: Graham Finch (2014) suggested that a "cost per R-value" be added to the Materials metric as this is a common request.

6.1.7 General Comments

Overall the metrics were deemed as successful in terms of identifying buildability in site-built, superinsulated wood framed assemblies in North America. Trevor Trainor stated—referring to the six metrics—"I think you have covered all of the major categories." The Question Sheet did not have guidelines for each of the questions and it was suggested by both Trainor and Finch that that the accuracy and usability of the tool would improve if examples for each question were derived. The layout of the Questions Sheet was also called into question. Trainor suggested he would like to see an "evaluation sheet" with the questions and a "user guide" to accompany and clarify the questions using the guidelines. The layout of the Evaluation Sheet and Revised User Guide follow Trainor's recommendations. The User Guide also contains guidelines for each and every question.

Finally, Cohen stated that instead of altering the design to be more buildable, the focus of the model would make more sense if its purpose was to find the best buildability for the design. This is a different perspective on what the model can do to identify characteristics of buildability, but it is simply the user's frame of mind when using the model and requires no alteration to either the Evaluation Sheet or the User Guide.

6.2 Potential Problems with this Method

Much of the research in this field has held a wider scope than this project. The research in this project is very specific to wood frame construction. The assemblies used to test this tool represent a relatively small proportion of the new homes built in North America each year. Because of this, the research regarding these assemblies—and specifically the buildability of these assemblies—is limited. This MRP is a first attempt at assessing buildability in wood framed, superinsulated wall assembles and is by no means definitive. Ideally, this tool would be able to assess both standard practice assemblies and innovative new assemblies alike. For innovative assemblies, however, it is assumed that the tool would have to be refined to address the assembly's new factors at this stage. This required tweaking of the tool is less than ideal. Ideally, the tool would have a broad enough scope that it could be successful at assessing the buildability of assemblies that have yet to been conceived. Creating a tool which is useful at assessing buildability of wood framed walls, using any assembly in any context would make the tool extremely versatile. Refining the tool to be more versatile is something to be undertaken in further research which is covered in section 6.3.

Another major flaw in the way this research was conducted is related to the resources available. Because buildability is highly contextual, only four out of the six metrics have been assessed. Though the industry experts looked at all six metrics and the associated questions, the Trades and Materials metrics have yet to be put to use on a case study. To compound the problem, both the assemblies and the experts are drawn from different contexts. An assessment of the tool that might produce more accurate results would involve assemblies and experts from the same context assessing the tool. For example, if twenty industry experts from the Toronto area, familiar with standard practice in Toronto and superinsulated wall assemblies, were to assess the revised tool, then six superinsulated assemblies from the Toronto were assessed by the tool, the conclusions drawn from the results would be more robust. As it stands, it is inappropriate to compare the four assemblies assessed by the tool, because not only is the tool in its infancy, but the context of each assembly is different, and therefore, comparisons between the case studies are compromised by their differing contexts.

Finally, the tool is subjective, as it asks the user to assess an assembly based on their own knowledge, experience and understanding of the detail drawings and building science. This subjectivity is not necessarily a bad thing, as this tool must be accessible to the user whether the user is a designer, a project manager or a building science professional. It would be impractical to have an objective tool for assessing wall assemblies, as there is such dramatic deviation between construction methods and within the context of each project. Being a subjective tool, one must be careful what conclusions are drawn from the results. The tool is intended to identify weaknesses in buildability; only if the same person assesses multiple assemblies using the tool, then would it be appropriate to draw any larger conclusions regarding the comparison between assemblies (keeping in mind that a specific assembly is being assessed and not an assembly type in general).

To address the subjectivity, a User Guide accompanies the tool Revised Tool (see Appendix VI). This User Guide contains every question and instructions or examples related to how the question should be scored. Unfortunately, the User Guide does not reflect context as it relates to the metrics and the questions. Therefore the scores identified in the User Guide are not always appropriate, as each question should be scored as it relates to the appropriate context of the metric being judged.

The only way to approach continuity in the results when using this tool is to have the same person assess multiple assemblies. By having the same person assessing a group of assemblies, one ensures that the knowledge assessing those assemblies comes from the same place, and that the assemblies can therefore be compared to each other. Though neither following the User Guide nor using the same person will make this tool objective, the comparison of the results will give the user a strong indication of which assemblies are better suited for their context and application. This tool should not be looked as the definitive answer regarding buildability as it related to an assembly, but rather an early attempt at the creation of a method for assessing different strengths and weaknesses of a potential assembly.

6.3 Future Work

The work included in this MRP is a starting point on a long road towards a tool which can successfully assess buildability in wood framed wall assemblies and do so with consistent results. Many of the flaws in the existing tool are mentioned above in section 6.2. The future work on the tool will consist of addressing many of the existing tool's shortcomings.

To date, the tool has assessed four complex assemblies, and the tool itself has been assessed by three industry professionals from three different contexts. There is too much variation in both the assemblies and the experts to draw any larger conclusions. The next step in refining this tool might be to focus the tool on a specific context. Find a larger sample of industry professionals from the same context and have them assess the revised tool. Have them assess the User Guide, the questions and the scores given for each question. Once the experts are happy with the tool, find a larger group of case studies from the same context as the industry professionals, and then assess the new assemblies. The results from the new case studies could then be handed over to the experts to ensure the tool was identifying appropriate strengths and weaknesses in the designs. This process would take much of the variation associated with context out of the question, and because of the continuity between the assemblies and the experts, the results from the tool will be more robust.

Another major downfall of the tool is that each question is not appropriate for every assembly. This means that for some assemblies, the results from one of the metrics are out of 15 and for others the results are out of 21. Though an assembly's score in a metric is averaged, this variation in the denominator will have an effect on the influence of each point awarded to an assembly. Work therefore needs to be done on the questions to ensure that each question is appropriate for every assembly. This plays into the weighting of the questions or the metrics. At this stage, neither the metrics nor the questions are weighted and because each metric is graphed separately, this weighting is unnecessary. However, as the tool is refined and the results become more accurate, it is assumed that the results from the tool will end up being generalized and compared. When comparing between overall assemblies and not simply between their metrics, weighting of the metrics becomes more important as some aspects of an assembly are more important than others. A system for the weighing of the metrics could be important to the future use of this tool.

Porter's 5 Force model was chosen because it was simple to use and could easily be manipulated, but there may be better methods and models for use with this tool. Future work should include research into other appropriate models that the tool could be based on.

CHAPTER 7: CONCLUSION

Straube's work on the topic of buildability identifies different superinsulated assemblies in general. The assemblies are assessed subjectively, and Straube's results in terms of their buildability are stated. His model isn't problematic because it is subjective—it's problematic because it is a generalization. Because of the context of a project, not every aspect of these assemblies can be generalized. There may be a situation where a where a Larsen Truss assembly would be more buildable than an exterior insulation assembly. Straube's suggestions regarding buildability in superinsulated assemblies are useful at a glance, but they do not touch on context or what specific aspects of an assembly are more or less buildable.

In this MRP, six metrics for buildability for wood framed wall assemblies were identified through interviews with industry professional familiar with superinsulated assemblies and from literature. They are working methods, time and components, potential for success, detail drawings, trades, and materials. Identifying these metrics leads to a deeper understanding of the factors related to the ease of construction of an assembly. By breaking down the metrics of buildability and the criteria that make up each metric, we can identify which aspects of an assembly will the least buildable. This tool is therefore more focused on assessing particular aspects of an assembly than the assembly as a whole. By identifying specific criteria and their overarching metrics, the associated problems in an assembly related to buildability can be improved. This improvement in buildability can have many positive outcomes including the performance of the assembly, the durability of the assembly, the amount of material used in the assembly, and ultimately, the cost of the assembly. All of these aspects lead towards a building that is easier to construct. The experts agreed that the metrics identified were appropriate for assessing buildability.

The six metrics can address every facet of buildability, but they need to be defined to do so. To use the six metrics in assessing a superinsulated assembly, a framework for assessment had to be established. The framework chosen for this MRP was Porter's 5 Forces model because of its simplicity as a model and the ease with which it can be adapted to reflect the source data. With the forces (metrics) of buildability established, questions related to each metric were created to clarify the metrics. Porter used a scale from 1-3 in his model for identifying the strength of weakness of his questions. In the case of this MRP, 1 represented a weak correlation to buildability and 3 represented a strong correlation to buildability. The information collected from the modified Porter model can then be graphed to show a visual representation of the results. The use of a graph makes the weakness related to the buildability of an assembly immediately obvious. Porter's model was helpful is creating a framework for assessing buildability, though it was the only model of its type considered. It would have been appropriate to asses a selection of models and see which was most appropriate. This was suggested in Future Works section 6.3.

Four case studies—the Jackman Residence, the Tree Eco-Village House, the Pedler Resident and the Fort St. John House—from *Passive House Design Details* (Richman, 2013) were evaluated using the tool. The results, which were evaluated against the literature on those assemblies, identified many of the weaknesses in the assemblies, but not all of them; for example, it missed pointing to potential moisture problems in the Tree Eco-Village House assembly. The model was therefore not a perfect success and must continue to be refined into a more precise tool. The overall method was a success; however, more analysis that can incorporate the Trades and Materials metrics is essential. As well, industry professions should review the Revised User Guide to ensure the efficacy and accuracy of the tool. The tool should then be used to assess a new series of case studies from the same context.

The results from the case studies show that both exterior insulation (the Jackman Residence) and double stud wall (the Tree Eco-Village) were highly buildable. This, however, is not necessarily true of these assemblies in general, but is true of only these specific assemblies used in this context. As well, the Trades and Materials metrics were not assessed. With local knowledge of the trades and availability of these materials the results could be different. The model is subjective and therefore assemblies should only be compared when they share the same local context and ideally when they are assessed by the same person.

The ultimate contribution of this MRP is the creation of the tool that is by no means definitive, but rather has opened a can of worms related to buildability in superinsulated assemblies. This tool requires further research to address its many shortcomings. The results from the tool are less significant than the creation of the tool itself. Even in its infancy, it is capable of identifying some weakness in a wall assembly. Though the tool is far from refined, the metrics related to buildability have been identified. Future work may include weighting the metrics related to their effect on buildability, but ultimately, the tool has some success in identifying weakness in an assembly. The Revised User Guide and Tool require significantly more study, and the work done with them requires more rigor, specifically using a variety of assemblies from the same context and having the tool assessed by professionals from that same context as the assemblies.

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Appendix I: Buildability Assessment Tool Question Sheet

Thank you for participating in the assessment of this model. The following is the tool created for assessing buildability in superinsulated, site built, wood framed wall assemblies in North America as a part of my major research project (MRP). A literature review was undertaken, and through it, six metrics of buildability were identified. For the purposes of this MRP, the definition of buildability is as follows:

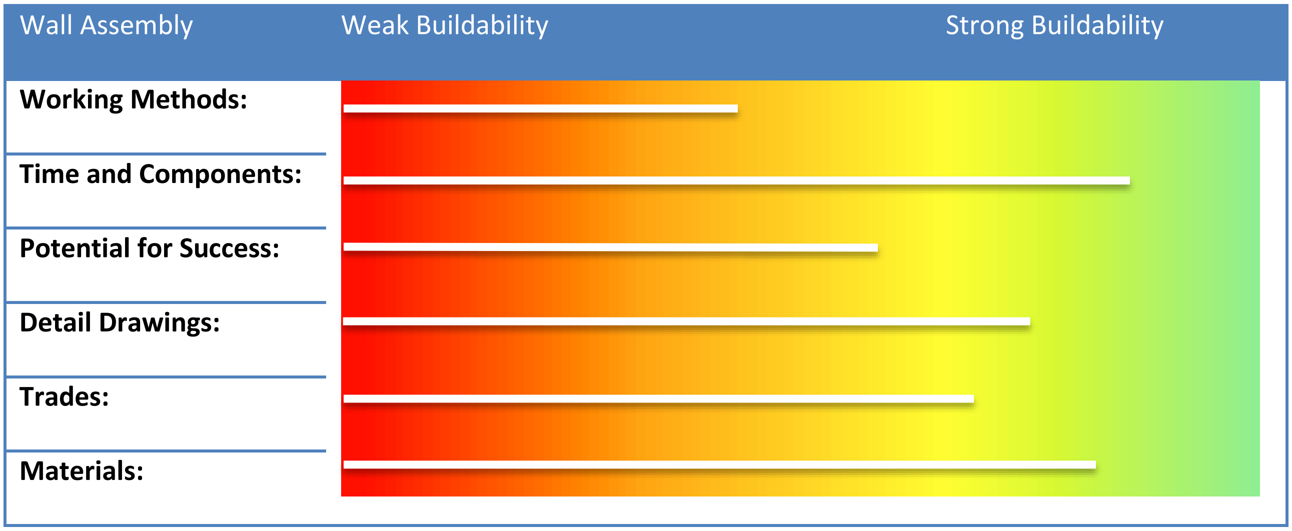
> *Buildability is the ease with which a project can be built as related to the working drawings, the experience of the trades, the workmanship required and the complexity of the building shape.*

This tool for assessing buildability has been loosely based on Porter's 5 Force Analysis model, which judges the five forces affecting market attractiveness. The five forces have been replaced with the six forces affecting buildability, which were identified in both literature and through four interviews with professionals in the industry who were experienced in building and designing superinsulated wall assemblies.

The six metrics are:

1. Working Methods
2. Time and Components
3. Potential for Success
4. Details
5. Trades
6. Materials

Metrics 1-3 are free from context and metrics 4-6 are highly related to the context of the geographical location. Each metric is judged using questions derived from deficiencies identified literature. The questions are designed to assess an assembly's buildability relative to said metric. Porter's method will be used as follows: 1 indicates a *weak relationship to buildability*, 2 indicates a *moderate relationship* and 3 indicates a *strong relationship to buildability*. Once assessed the averages of the results for each metric will be plotted on a graph similar to the one below. This will create a visual representation for the buildability of an assembly relative to the six identified metrics. This tool is highly subjective and therefore will create results which will reflect a specific design in a specific context and the education and experience of the participant using the tool.



Please respond on the following six attributes of the model:

1. Could you comment on the appropriateness of the metrics that have been identified?
2. Could you comment on the effectiveness of each metric's sub-questions? Do these questions seem, to you, to be central to their associated metric?
3. Could you comment on the usefulness of this tool for assessing buildability? Is the tool an appropriate length?
4. Would a member of your staff be able to answer all these questions?
5. Is anything about the assessment tool unclear? Or, is anything missing?
6. Do you have any other comments, positive or negative, that you'd like to pass along?

Metric 1: Working Methods

"Working methods" consider the way in which a structure is being built. Working method is the major factor related to buildability, as identified from literature to be *deviation from standard practice*. The aspects of the working method metric will be compared to a standard practice wall—the common, code compliant wall built in the region where the superinsulated assembly is to be constructed. Many superinsulated assemblies include components or methods which do not reflect industry practice and therefore are less buildable and will receive a higher score.

1	Working Methods:	Brief description of factor	Strength
1.1	Deviation from standard practice	Does the assembly reflect a traditional code built stick frame wall assembly?	
1.2	Prefabrication	Are there facets of the assembly which are built off site?	
1.3	Lumber	Are the pieces used in the assembly of the dimensions used in common practice?	
1.4	Fasteners	Are components attached using practices common to those constructing the assembly?	
1.5	Insulation installation	In the insulation common and is it applied in the usual manner?	

Question 1.1: Wall Assembly Type	Score
Standard practice—perfectly constructable as defined in literature	3
Exterior insulation, double stud—each case includes a standard practice wall as the structure	2
Vertical TJI—if TJIs are used as part of a truss system with a standard structural wall, then the score is 2; however, if TJI are used as the structure, this is a considerable deviation and therefore 1.	1-2

Question 1.2: Prefabrication (Larsen truss specific)	Score
100% prefabricated	3
Cut to length on site	2
100% site built	1

Question 1.3: Lumber	Score
Conventional lumber sizes – "2 by"	3
Lumber not used in common practice	1

Question 1.4: Fasteners	Score
Fasteners used in conventional framing	3
Deviation from standard fasteners	1

Question 1.5: Insulation Installation	Score
Batt insulation and spray foam between studs up to 6” or exterior rigid less than 1” thick	3
Dense pack cellulose, batt in a deep cavity wall and exterior rigid thicker than 1”	2
Rigid insulation within a cavity; baffled cavities for cellulose	1

Metric 2: Time and Components

An assembly which takes longer to construct or requires more components is, by definition, less buildable. The time variable for this factor can be derived from literature or experience. As well, in terms of time, it can be assumed that, the more complex the design, the more time is required. This complexity in design would include connections at other than 90°, cantilevers, inside corners and exposed floors.

In terms of components, which can be measured, the superinsulated assembly will be compared to a standard 2x6” code compliant wall section measuring 8’x8’. The volume of wood and insulation or area of sheathing, gypsum and membranes will be calculated and compared to those in a code wall. Assemblies requiring significantly more materials than the code wall will be seen a less buildable.

2	Time and Components	Brief description of factor	Strength
2.1	Time	Does assembly require additional time?	
2.2	Wood	How many cubic feet of wood are required in an 8x8’ section of this assembly?	
2.3	TJIs	What is the spacing of the TJIs in an 8x8’ section of this assembly?	
2.4	Sheathings	How many sheets of sheathing are required in an 8x8’ section of this assembly?	
2.5	Insulation	How many cubic feet of insulation are required in this assembly in an 8x8’ section of this assembly?	
2.6	Membrane	How many membranes are required for this assembly in an 8x8’ section of this assembly?	

In terms of time, an increase of 1-5% will be considered a 2 and from 5-10% will be considered a 1. Any small increases in component and volume will receive a 2 and any increases above 40% of code wall volume or area will receive a 1.

Metric 3: Potential for Success

A superinsulated wall's potential for success in terms of buildability can be determined by identifying the shortcomings in its style of assembly as described in literature.

3	Potential for Success	Brief description of factor	Strength
3.1	Additional details	Does the complexity of the assembly require additional details?	
3.2	Susceptibility to deficiencies	Is this assembly known for its susceptibility to failure? (i.e. collecting water)	
3.3	Connections	Are the connections between components reliable, supported, redundant and effective?	
3.4	Code	Is the wall code compliant?	

Question 3.1: Additional Details	Score
If the assembly only requires details which are standard practice	3
Some assemblies have details which would be considered similar to best practice details in a code assembly i.e. double stud wall	2
Some assemblies require details that vary from standard practice i.e. exterior insulation	1

Question 3.2: Susceptibility to deficiencies	Score
Some superinsulated assemblies are not known for moisture problems	3
Some have an cavity outboard of the structure which are known for potential moisture problems, but not within the structural cavity	2
Some assemblies are known for moisture problems in the same cavity as the structure	1

Metric 4: Details

Details are the first of the contextual metrics. For this section, specific details related to the assembly will be assessed to determine their buildability. Much of the literature states the importance of quality details regarding both superinsulated assemblies and buildability success. Details must relay information in a visual and written from to those who will be constructing the assembly. In the case of superinsulation and specifically Passive House, there is little room for error. Therefore, for the details to be buildable they must be clear and unambiguous, showing and telling a specific progression towards success. Explicit details with no room for interpretation will be considered highly buildable; details lacking that precision will be considered less so.

4	Details	Brief description of factor	Strength
4.1	Barriers and retarders	Are all barriers/retarders visible in the details including clear instructions as to their sequencing in the assembly and the application?	
4.2	Continuity	Is the continuity of the insulation and the membranes addressed visually and in written form in the details? Is the insulation within the same plane?	
4.3	Simplicity	Have the details been simplified to exaggerate the most important aspects of the construction?	
4.4	Required details	Are there specific details for all of the following which apply? Window/door header, window/door casement, window sill, foundation/slab meets wood framing, wall meets second floor, wall meets roof, outside corner, inside corner and penetrations	

Unlike Metrics 1-3, for Metric 4, a standard practice detail would be given a 3—reflective of weak buildability—because superinsulated assemblies require more precision than a standard practice detail provides.

Metric 5: Trades

The trades and their experience and knowledge regarding assembly constructions methods and low energy buildings is essential to on-site problem solving (though ideally problem solving is done off site). Superinsulated assemblies by definition differ from standard practice. Many include advanced framing and a standard for airtight envelopes which may be unfamiliar to tradespeople used to working on code buildings. This gap in knowledge requires education and dedication by the trades to the final result. This is a very contextual factor of buildability and therefore would be impossible to assess without either experience building in the area in which the home will be constructed or experience with the trades in the area. Literature has identified many of the factors which affect the trades on a job.

5	Trades	Brief description of factor	Strength
5.1	Experience	Have the trades worked with this method before? Do they have experience using advanced framing?	
5.2	Education	Are the trades educated regarding building envelopes and energy efficiency?	
5.3	Inclusion	Were the trades included in the design process? Is there an open line of communication between the trades and the designer/consultant?	
5.4	Workmanship	Do the trades have high standards of performance?	

Metric 6: Materials

As with the trades, materials are contextual. Availability of materials and the experience of the tradespeople working with those materials are essential to buildability. As well, the size and weight of the materials is an important factor in buildability. If additional resources are required to complete an assembly, the assembly would be considered less buildable.

6	Materials	Brief description of factor	Strength
6.1	Availability	Are the materials available in your area?	
6.2	Experience of the trades	Are the local tradespeople familiar with working with these materials?	
6.3	Cumbersome	Are the materials larger or heavier than those traditionally used on site?	
6.4	Machinery	Does the application of these materials require any additional equipment such as scaffolding, a crane or a blower for cellulose which is not used in standard practice?	

Question 6.4: Machinery	Score
No additional machinery, resources required	1
Scaffolding or crane required for wall assembly	2
Scaffolding and crane required for wall assembly	3

Appendix II: Completed Question Sheet – Jackman Residence

1	Working Methods:	Brief description of factor	Strength
1.1	Deviation from standard practice	Does the assembly reflect a traditional code built stick frame wall assembly?	2
1.2	Prefabrication	Are there facets of the assembly which are built off site?	N/A
1.3	Lumber	Are the pieces used in the assembly of the dimensions used in common practice?	3
1.4	Fasteners	Are components attached using practices common to those constructing the assembly?	1
1.5	Insulation installation	In the insulation common and is it applied in the usual manner?	2

2	Time and Components	Brief description of factor	Strength
2.1	Time	Does assembly require additional time?	2
2.2	Wood	How many cubic feet of wood are required in an 8x8' section of this assembly?	2
2.3	TJIs	What is the spacing of the TJIs in an 8x8' section of this assembly?	N/A
2.4	Sheathings	How many sheets of sheathing are required in an 8x8' section of this assembly?	3
2.5	Insulation	How many cubic feet of insulation are required in this assembly in an 8x8' section of this assembly?	2
2.6	Membrane	How many membranes are required for this assembly in an 8x8' section of this assembly?	2

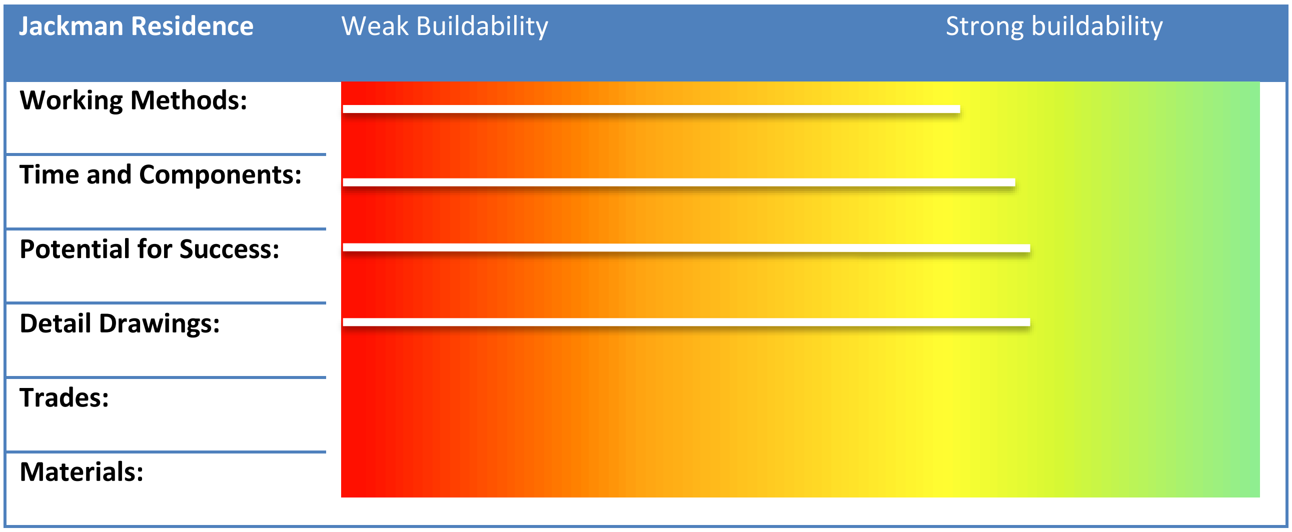
3	Potential for Success	Brief description of factor	Strength
3.1	Additional details	Does the complexity of the assembly require additional details?	2
3.2	Susceptibility to deficiencies	Is this assembly known for its susceptibility to failure? (i.e. collecting water)	3
3.3	Connections	Are the connections between components reliable, supported, redundant and effective?	2
3.4	Code	Is the wall code compliant?	3

4	Detail Drawings	Brief description of factor	Strength
4.1	Barriers and retarders	Are all barriers/retarders visible in the details including clear instructions as to their sequencing in the assembly and the application?	2
4.2	Continuity	Is the continuity of the insulation and the membranes addressed visually and in written form in the details? Is the insulation within the same plane?	2
4.3	Simplicity	Have the details been simplified to exaggerate the most important aspects of the construction?	3
4.4	Required details	Are there specific details for all of the following which apply? Window/door header, window/door casement, window sill, foundation/slab meets wood framing, wall meets second floor, wall meets roof, exposed floors, balconies, outside corner, inside corner and penetrations	2

5	Trades	Brief description of factor	Strength
5.1	Experience	Have the trades worked with this method before? Do they have experience using advanced framing?	
5.2	Education	Are the trades educated regarding building envelopes and energy efficiency?	
5.3	Inclusion	Were the trades included in the design process? Is there an open line of communication between the trades and the designer/consultant?	
5.4	Workmanship	Do the trades have high standards of performance?	

6	Materials	Brief description of factor	Strength
6.1	Availability	Are the materials available in your area?	
6.2	Experience of the trades	Are the local tradespeople familiar with working with these materials?	
6.3	Cumbersome	Are the materials larger or heavier than those traditionally used on site?	
6.4	Machinery	Does the application of these materials require any additional equipment such as scaffolding, a crane or a blower for cellulose which is not used in standard practice?	

Metric	1	2	3	4	5	6
Score	8/12	11/15	10/12	9/12	N/A	N/A



Appendix III: Completed Question Sheet – Tree Eco-Village

1	Working Methods:	Brief description of factor	Strength
1.1	Deviation from standard practice	Does the assembly reflect a traditional code built stick frame wall assembly?	2
1.2	Prefabrication	Are there facets of the assembly which are built off site?	N/A
1.3	Lumber	Are the pieces used in the assembly of the dimensions used in common practice?	3
1.4	Fasteners	Are components attached using practices common to those constructing the assembly?	3
1.5	Insulation installation	In the insulation common and is it applied in the usual manner?	1

2	Time and Components	Brief description of factor	Strength
2.1	Time	Does assembly require additional time?	1
2.2	Wood	How many cubic feet of wood are required in an 8x8' section of this assembly?	1
2.3	TJIs	What is the spacing of the TJIs in an 8x8' section of this assembly?	N/A
2.4	Sheathings	How many sheets of sheathing are required in an 8x8' section of this assembly?	3
2.5	Insulation	How many cubic feet of insulation are required in this assembly in an 8x8' section of this assembly?	1
2.6	Membrane	How many membranes are required for this assembly in an 8x8' section of this assembly?	2

3	Potential for Success	Brief description of factor	Strength
3.1	Additional details	Does the complexity of the assembly require additional details?	2
3.2	Susceptibility to deficiencies	Is this assembly known for its susceptibility to failure? (i.e. collecting water)	3
3.3	Connections	Are the connections between components reliable, supported, redundant and effective?	2
3.4	Code	Is the wall code compliant?	3

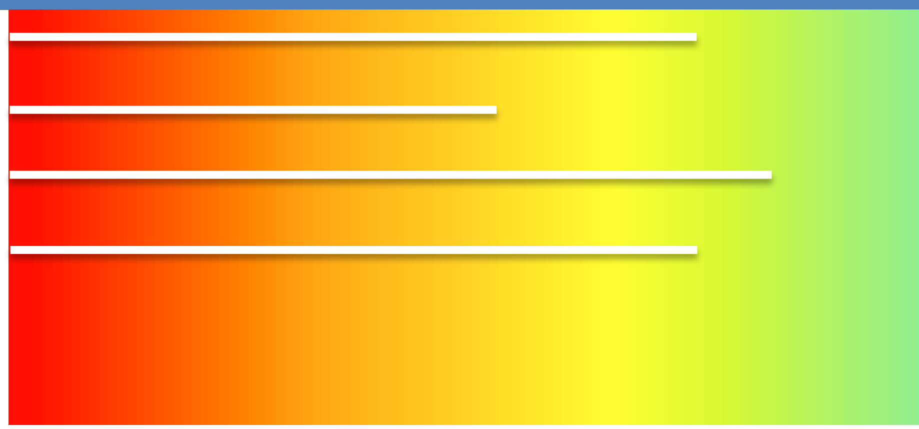
4	Detail Drawings	Brief description of factor	Strength
4.1	Barriers and retarders	Are all barriers/retarders visible in the details including clear instructions as to their sequencing in the assembly and the application?	2
4.2	Continuity	Is the continuity of the insulation and the membranes addressed visually and in written form in the details? Is the insulation within the same plane?	2
4.3	Simplicity	Have the details been simplified to exaggerate the most important aspects of the construction?	2
4.4	Required details	Are there specific details for all of the following which apply? Window/door header, window/door casement, window sill, foundation/slab meets wood framing, wall meets second floor, wall meets roof, exposed floors, balconies, outside corner, inside corner and penetrations	3

5	Trades	Brief description of factor	Strength
5.1	Experience	Have the trades worked with this method before? Do they have experience using advanced framing?	
5.2	Education	Are the trades educated regarding building envelopes and energy efficiency?	
5.3	Inclusion	Were the trades included in the design process? Is there an open line of communication between the trades and the designer/consultant?	
5.4	Workmanship	Do the trades have high standards of performance?	
5.5	Sequencing	What is the sequencing of the trades?	

6	Materials	Brief description of factor	Strength
6.1	Availability	Are the materials available in your area?	
6.2	Experience of the trades	Are the local tradespeople familiar with working with these materials?	
6.3	Cumbersome	Are the materials larger or heavier than those traditionally used on site?	
6.4	Machinery	Does the application of these materials require any additional equipment such as scaffolding, a crane or a blower for cellulose which is not used in standard practice?	
6.5	Cost per R-value		

Metric	1	2	3	4	5	6
Score	9/12	8/15	10/12	9/12	N/A	N/A

Tree Eco-Village	Weak Buildability	Strong Buildability
Working Methods:		
Time and Components:		
Potential for Success:		
Detail Drawings:		
Trades:		
Materials:		



Appendix IV: Completed Question Sheet – Pedler Residence

1	Working Methods:	Brief description of factor	Strength
1.1	Deviation from standard practice	Does the assembly reflect a traditional code built stick frame wall assembly?	2
1.2	Prefabrication	Are there facets of the assembly which are built off site?	3
1.3	Lumber	Are the pieces used in the assembly of the dimensions used in common practice?	3
1.4	Fasteners	Are components attached using practices common to those constructing the assembly?	1
1.5	Insulation installation	In the insulation common and is it applied in the usual manner?	2

2	Time and Components	Brief description of factor	Strength
2.1	Time	Does assembly require additional time?	1
2.2	Wood	How many cubic feet of wood are required in an 8x8' section of this assembly?	3
2.3	TJIs	What is the spacing of the TJIs in an 8x8' section of this assembly?	N/A
2.4	Sheathings	How many sheets of sheathing are required in an 8x8' section of this assembly?	2
2.5	Insulation	How many cubic feet of insulation are required in this assembly in an 8x8' section of this assembly?	1
2.6	Membrane	How many membranes are required for this assembly in an 8x8' section of this assembly?	2

3	Potential for Success	Brief description of factor	Strength
3.1	Additional details	Does the complexity of the assembly require additional details?	2
3.2	Susceptibility to deficiencies	Is this assembly known for its susceptibility to failure? (i.e. collecting water)	1
3.3	Connections	Are the connections between components reliable, supported, redundant and effective?	2
3.4	Code	Is the wall code compliant?	3

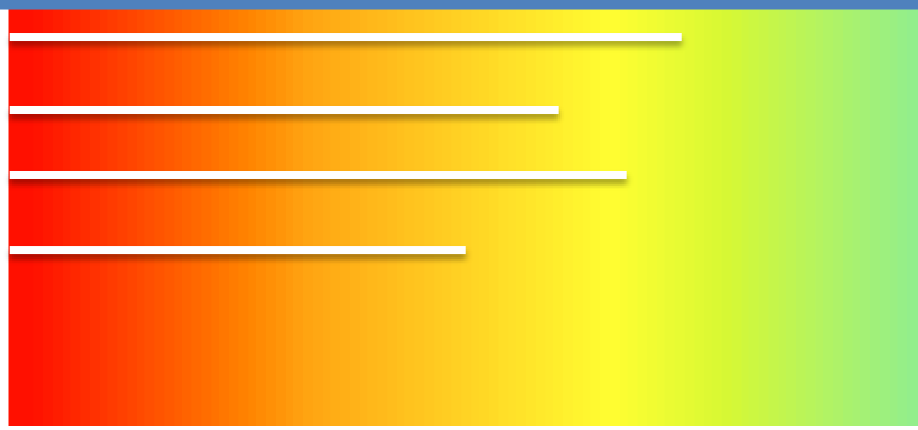
4	Detail Drawings	Brief description of factor	Strength
4.1	Barriers and retarders	Are all barriers/retarders visible in the details including clear instructions as to their sequencing in the assembly and the application?	2
4.2	Continuity	Is the continuity of the insulation and the membranes addressed visually and in written form in the details? Is the insulation within the same plane?	1
4.3	Simplicity	Have the details been simplified to exaggerate the most important aspects of the construction?	2
4.4	Required details	Are there specific details for all of the following which apply? Window/door header, window/door casement, window sill, foundation/slab meets wood framing, wall meets second floor, wall meets roof, exposed floors, balconies, outside corner, inside corner and penetrations	1

5	Trades	Brief description of factor	Strength
5.1	Experience	Have the trades worked with this method before? Do they have experience using advanced framing?	
5.2	Education	Are the trades educated regarding building envelopes and energy efficiency?	
5.3	Inclusion	Were the trades included in the design process? Is there an open line of communication between the trades and the designer/consultant?	
5.4	Workmanship	Do the trades have high standards of performance?	
5.5	Sequencing	What is the sequencing of the trades?	

6	Materials	Brief description of factor	Strength
6.1	Availability	Are the materials available in your area?	
6.2	Experience of the trades	Are the local tradespeople familiar with working with these materials?	
6.3	Cumbersome	Are the materials larger or heavier than those traditionally used on site?	
6.4	Machinery	Does the application of these materials require any additional equipment such as scaffolding, a crane or a blower for cellulose which is not used in standard practice?	
6.5	Cost per R-value		

Metric	1	2	3	4	5	6
Score	11/15	9/15	8/12	6/12	N/A	N/A

Pelder Residence	Weak Buildability	Strong Buildability
Working Methods:		
Time and Components:		
Potential for Success:		
Detail Drawings:		
Trades:		
Materials:		



Appendix V: Completed Question Sheet – Fort St. John

1	Working Methods:	Brief description of factor	Strength
1.1	Deviation from standard practice	Does the assembly reflect a traditional code built stick frame wall assembly?	1
1.2	Prefabrication	Are there facets of the assembly which are built off site?	N/A
1.3	Lumber	Are the pieces used in the assembly of the dimensions used in common practice?	1
1.4	Fasteners	Are components attached using practices common to those constructing the assembly?	3
1.5	Insulation installation	In the insulation common and is it applied in the usual manner?	2

2	Time and Components	Brief description of factor	Strength
2.1	Time	Does assembly require additional time?	1
2.2	Wood	How many cubic feet of wood are required in an 8x8' section of this assembly?	3
2.3	TJIs	What is the spacing of the TJIs in an 8x8' section of this assembly?	3
2.4	Sheathings	How many sheets of sheathing are required in an 8x8' section of this assembly?	2
2.5	Insulation	How many cubic feet of insulation are required in this assembly in an 8x8' section of this assembly?	1
2.6	Membrane	How many membranes are required for this assembly in an 8x8' section of this assembly?	2

3	Potential for Success	Brief description of factor	Strength
3.1	Additional details	Does the complexity of the assembly require additional details?	2
3.2	Susceptibility to deficiencies	Is this assembly known for its susceptibility to failure? (i.e. collecting water)	1
3.3	Connections	Are the connections between components reliable, supported, redundant and effective?	2
3.4	Code	Is the wall code compliant?	1

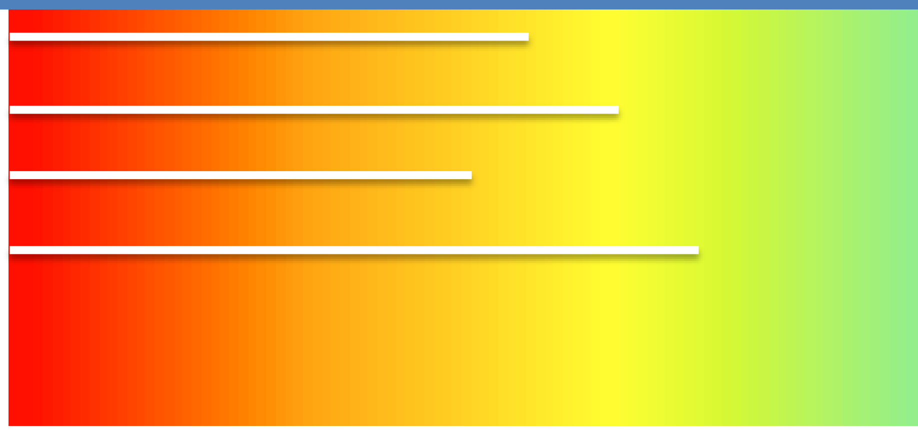
4	Detail Drawings	Brief description of factor	Strength
4.1	Barriers and retarders	Are all barriers/retarders visible in the details including clear instructions as to their sequencing in the assembly and the application?	2
4.2	Continuity	Is the continuity of the insulation and the membranes addressed visually and in written form in the details? Is the insulation within the same plane?	1
4.3	Simplicity	Have the details been simplified to exaggerate the most important aspects of the construction?	3
4.4	Required details	Are there specific details for all of the following which apply? Window/door header, window/door casement, window sill, foundation/slab meets wood framing, wall meets second floor, wall meets roof, exposed floors, balconies, outside corner, inside corner and penetrations	3

5	Trades	Brief description of factor	Strength
5.1	Experience	Have the trades worked with this method before? Do they have experience using advanced framing?	
5.2	Education	Are the trades educated regarding building envelopes and energy efficiency?	
5.3	Inclusion	Were the trades included in the design process? Is there an open line of communication between the trades and the designer/consultant?	
5.4	Workmanship	Do the trades have high standards of performance?	
5.5	Sequencing	What is the sequencing of the trades?	

6	Materials	Brief description of factor	Strength
6.1	Availability	Are the materials available in your area?	
6.2	Experience of the trades	Are the local tradespeople familiar with working with these materials?	
6.3	Cumbersome	Are the materials larger or heavier than those traditionally used on site?	
6.4	Machinery	Does the application of these materials require any additional equipment such as scaffolding, a crane or a blower for cellulose which is not used in standard practice?	
6.5	Cost per R-value		

Metric	1	2	3	4	5	6
Score	7/12	12/18	6/12	9/12	N/A	N/A

Fort St. John	Weak Buildability	Strong Buildability
Working Methods:		
Time and Components:		
Potential for Success:		
Detail Drawings:		
Trades:		
Materials:		



Appendix VI: Evaluation Sheet and Revised User Guide

Evaluation Sheet

The following tool is designed for assessing buildability in current North American residential construction as it relates to a specific project in a specific context. Though the tool is highly subjective, explanations or examples for each of the questions have been provided to clarify the questions and limit wild deviation between assessments. For the best results, assemblies should be assessed by an appropriate professional with knowledge of related to the assemblies and the area. Outcomes for competing assembles should be compared to each other. The metrics are to be judged on a scale of 1-3: 1 indicates a *strong relationship to buildability*, 2 indicates a *moderate relationship* and 3 indicates a *weak relationship to buildability*.

1	Working Methods:	Brief description of factor	Strength
1.1	Deviation from standard practice	Does the assembly reflect a traditional code built stick frame wall assembly?	
1.2	Prefabrication	Are there facets of the assembly which are built off site?	
1.3	Lumber	Are the pieces used in the assembly of the dimensions used in common practice?	
1.4	Fasteners	Are components attached using practices common to those constructing the assembly?	
1.5	Insulation installation	In the insulation common and is it applied in the usual manner?	

2	Time and Components:	Brief description of factor	Strength
2.1	Time	Does assembly require additional time?	
2.2	Wood	How many cubic feet of wood are required in an 8x8’ section of this assembly?	
2.3	TJIs	What is the spacing of the TJIs in an 8x8’ section of this assembly?	
2.4	Sheathings	How many sheets of sheathing are required in an 8x8’ section of this assembly?	
2.5	Insulation	How many cubic feet of insulation are required in this assembly in an 8x8’ section of this assembly?	
2.6	Membrane	How many membranes are required for this assembly in an 8x8’ section of this assembly?	
2.7	Weight	What is the overall weight of an 8x8’ section of this assembly?	
2.8	Thickness	What is the overall thickness of the wall assembly?	

3	Potential for Success:	Brief description of factor	Strength
3.1	Additional details	Does the complexity of the assembly require additional details?	
3.2	Wetting potential	What is the assemblies wetting of the assembly?	
3.3	Drying potential	What is the drying potential for the assembly?	
3.4	Durability	What is the durability potential for the assembly?	
3.5	Connections	Are the connections between components reliable, supported, redundant and effective?	
3.6	Code	Is the wall code compliant?	
3.7	Commissioning	Will the building envelope be commissioned?	

4	Detail Drawings:	Brief description of factor	Strength
4.1	Barriers and retarders	Are all barriers/retarders visible in the details including clear instructions as to their sequencing in the assembly and the application?	
4.2	Continuity	Is the continuity of the insulation and the membranes addressed visually and in written form in the details? Is the insulation within the same plane?	
4.3	Simplicity	Have the details been simplified to exaggerate the most important aspects of the construction?	
4.4	Required details	Are there specific details for all of the following which apply? Window/door header, window/door casement, window sill, foundation/slab meets wood framing, wall meets second floor, wall meets roof, exposed floors, balconies, outside corner, inside corner and penetrations	

5	Trades:	Brief description of factor	Strength
5.1	Experience	Have the trades worked with this method before? Do they have experience using advanced framing?	
5.2	Education	Are the trades educated regarding building envelopes and energy efficiency?	
5.3	Inclusion	Were the trades included in the design process? Is there an open line of communication between the trades and the designer/consultant?	
5.4	Workmanship	Do the trades have high standards of performance?	
5.5	Sequencing	What is the sequencing of the trades?	

6	Materials:	Brief description of factor	Strength
6.1	Availability	Are the materials available in your area?	
6.2	Experience of the trades	Are the local tradespeople familiar with working with these materials?	
6.3	Cumbersome	Are the materials larger or heavier than those traditionally used on site?	
6.4	Machinery	Does the application of these materials require any additional equipment such as scaffolding, a crane or a blower for cellulose which is not used in standard practice?	
6.5	Cost per R-value	What is the cost per 1” thickness of wall?	

Revised User Guide

Metric 1: Working Methods

"Working methods" consider the way in which a structure is being built. Working method is the major factor related to buildability, as identified from literature to be *deviation from standard practice*. The aspects of the working method metric will be compared to a standard practice wall—the common, code compliant wall built in the region where the superinsulated assembly is to be constructed. Many superinsulated assemblies include components or methods which do not reflect industry practice and therefore are less buildable and will receive a higher score.

Question 1.1: Wall Assembly Type	Score
Standard practice—perfectly constructable as defined in literature	3
Exterior insulation, double stud, Larsen truss—each case includes a standard practice wall as the structure	2
Vertical TJI—if TJIs are used as part of a truss system with a standard structural wall, then the score is 2; however, if TJI are used as the structure, this is a considerable deviation and therefore 3.	1-2

Question 1.2: Prefabrication (Larsen truss specific)	Score
100% prefabricated	3
Cut to length on site	2
100% site built	1

Question 1.3: Lumber	Score
Conventional lumber sizes – "2 by"	3
Lumber not used in common practice for structure	1

Question 1.4: Fasteners	Score
Fasteners used in conventional framing	3
Deviation from standard fasteners	1

Question 1.5: Insulation Installation	Score
Cellulose or batt insulation up to 6" or exterior rigid less than 1" thick	3
Dense pack cellulose or batt in a deep cavity wall, exterior rigid thicker than 1" and spray foam requiring one application	2
Rigid insulation within a cavity; baffled cavities for cellulose applications or spray foam with a thickness which requires multiple site visits	1

Metric 2: Time and Components

An assembly which takes longer to construct or requires more components is, by definition, less buildable. The time variable for this factor can be derived from literature or experience. As well, in terms of time, it can be assumed that, the more complex the design, the more time is required. This complexity in design would include connections at other than 90°, cantilevers, inside corners and exposed floors.

In terms of components, which can be measured, the superinsulated assembly will be compared to a standard 2x6" code compliant wall section measuring 8'x8'. The volume of wood and insulation or area of sheathing, gypsum and membranes will be calculated and compared to those in a code wall. Assemblies requiring significantly more materials than the code wall will be seen a less buildable.

Question 2.1: Time	Score
No increase in time	3
An increase in time of 1-5%	2
An increase in time of 5-10%	1

Question 2.2: Wood	Score
No increase in structural framing	3
An increase in structural framing of up to 20%	2
An increase in structural framing of above 20%	1

Question 2.3: TJIs (if applicable)	Score
Spacing at 24" o/c	3
Spacing at 16" o/c	2
Spacing at 12" o/c	1

Question 2.4: Sheathings	Score
No increase in sheathing	3
An increase of 2 sheets of sheathing	2
An increase of 4 sheets of sheathing	1

Question 2.5: Insulation	Score
No increase in insulation	3
An increase of up to 100% in insulation	2
An increase of above 100% in insulation	1

Question 2.6: Membrane	Score
One or fewer membranes	3
Two membranes	2
Three or more membranes	1

Question 2.7: Weight	Score
No change in the assemblies weight	3
An increase of less than 100% in weight	2
An increase over 100% in weight	1

Question 2.8: Thickness	Score
No increase in thickness	3
An increase in thickness of less than 150%	2
An increase in thickness of over 150%	1

Metric 3: Potential for Success

A superinsulated wall's potential for success in terms of buildability can be determined by identifying the shortcomings in its style of assembly as described in literature.

Question 3.1: Additional Details	Score
If the assembly only requires details which are standard practice	3
Some assemblies have details which would be considered similar to best practice details in a code assembly i.e. double stud wall	2
Some assemblies require details that vary from standard practice i.e. exterior insulation	1

Question 3.2: Wetting Potential	Score
The assembly is not known to have problems associated with the collection of water through, for example, complexity of water control features, continuity of the air barrier or the 'cold OSB' phenomenon.	3
The assembly is known for potential problems associated with the collection of water, but not in the cavity which contains the structure.	2
The assembly is known for having problems associated with the collection of water in the same cavity/close proximity to the structure.	1

Question 3.3: Drying Potential	Score
Does the wall have a high potential for drying in both directions, for example highly vapour permeable materials allowing for drying from the interior and exterior?	3
Does the wall have high drying potential in only one direction?	2
Does the wall have poor drying potential in both directions, for example a vapour trap?	1

Question 3.4: Durability	Score
The wall is designed to dry and flashing or other exterior features deflect water away from the structure. It is constructed of materials which resist mold and rot. It uses materials which have a long lifespan and its membranes are continuous. It has 2' or greater overhangs from the roof.	3
The wall is not designed with an eye to durability.	1

Question 3.5: Connections	Score
All four aspects of: reliable, supported, redundant and effective have been addressed for connections between two materials.	3
Two of the four aspects of: reliable, supported, redundant and effective have been addresses i.e. air barrier is sandwiched between sheathing and exterior insulation so it is supported, and reliable, but the insulation is open cell and the seams of the insulation are not sealed so it is not redundant and window flashing does not have end dams so it is not effective.	2
Standard practice connections i.e. air barrier stapled to the exterior sheathing with seams sealed in tuck tape, sill gasket between foundation wall and sill plate…	1

Question 3.6: Code	Score
The assembly is code compliant as it stands	3
The assembly requires a review to be code compliant	1

Question 3.7: Commissioning	Score
The building will receive commissioning including multiple blower door test and thermal imaging at specific stages during the constructions	3
The building receive commissioning including both a bower door test and a thermal imaging camera	2
The building will not be commissioned	1

Metric 4: Detail Drawings

For this section, specific detail drawings related to the assembly will be assessed to determine their buildability. Details must relay information in a visual and written from to those who will be constructing the assembly. In the case of superinsulation and specifically Passive House, there is little room for error. Therefore, for the details to be buildable they must be clear and unambiguous, showing and telling a specific progression towards success. Explicit details with no room for interpretation will be considered highly buildable; details lacking that precision will be considered less so.

Unlike Metrics 1-3, for Metric 4, a standard practice detail would be given a 3—reflective of weak buildability—because superinsulated assemblies require more precision than a standard practice detail provides. The details which should be judged for this metric are corners, windows and other penetrations requiring framing. Details should be judged separately and the results averaged.

Question 4.1: Barriers and Retarders	Score
Membranes are exaggerated in the drawing with clear definition of their application in terms of lapping. The sequencing of the membranes is explained in words in the notes.	3
The membranes are exaggerated but lack either the written instruction or visual definition regarding the sequencing of their application.	2
Membranes appear simply as a line with no explanation	1

Question 4.2: Continuity	Score
The insulation appears in a continuous plane at junctions and its application at junctions is explained visually and in words.	3
The insulation remains continuous at junctions though it may shift planes as represented in the working drawings.	2
The insulation is not in a continuous plane at junctions	1

Question 4.3: Simplicity	Score
The details are easy to implement and repeat successfully around the entire envelope.	3
The details are either easy to implement or they are repeatable, but not both.	2
The details are neither easy to implement or easy to repeat successfully.	1

Question 4.4: Required Details	Score
The working drawings contain all of the appropriate details mentioned in the question	3
The working drawings contain 80% of the appropriate details mentioned	2
The working drawings contain fewer than 80% of the appropriate details mentioned	1

Metric 5: Trades

The trades and their experience and knowledge regarding assembly constructions methods and low energy buildings is essential to on-site problem solving (though ideally problem solving is done off site). Superinsulated assemblies by definition differ from standard practice. Many include advanced framing and a standard for airtight envelopes which may be unfamiliar to tradespeople used to working on code buildings. This gap in knowledge requires education and dedication by the trades to the final result. This is a very contextual factor of buildability and therefore would be impossible to assess without either experience building in the area in which the home will be constructed or experience with the trades in the area. Literature has identified many of the factors which affect the trades on a job.

Question 5.1: Experience	Score
The trades have experience from more than one of these assemblies	3
The trades have only worked on an assembly such as this once before	2
This is the trades first interdiction to this assembly	1

Question 5.2: Education	Score
The trades are well versed in advanced envelopes	3
The trades have some education related to advanced envelopes	2
The tradespeople know nothing regarding advanced envelopes	1

Question 5.3: Inclusion	Score
The trades were a part of the design team and contributed greatly	3
The trades were included in the design process	2
The trades were left out of the design process	1

Question 5.1: Workmanship	Score
The trades understand the importance of their jobs and have high performance standards	3
The trades have relatively high performance standards	2
The trades have relatively low performance standards	1

Question 5.5: Sequencing	Score
A plan for the sequencing of assembly has been created and shared with the trades ensuring the trades will not have to be called back to the site once they have completed their specific task.	3
A plan for the sequencing of assembly has been created and shared with the trades and a minimum of trades will have to make multiple site visits.	2
There is no plan in terms of sequencing and the trades are called to site as needed	1

Metric 6: Materials

As with the trades, materials are contextual. Availability of materials and the experience of the tradespeople working with those materials are essential to buildability. As well, the size and weight of the materials is an important factor in buildability. If additional resources are required to complete an assembly, the assembly would be considered less buildable.

Question 6.1: Availability	Score
The materials are readily available in the area	3
The materials can be brought in	2
The materials are unavailable in this area and must be ordered from afar	1

Question 6.2: Experience of the trades	Score
These are all materials which the trades work with every day	3
80% of the materials are those which the trades work with every day	2
Less than 80% of the materials are those which the trades work with	1

Question 6.3: Cumbersome	Score
The materials are of a size or weight common to practice	3
The materials are heavier or larger than common practice	2
The materials cannot be moved as would be the case in common practice	1

Question 6.4: Machinery	Score
No additional machinery, resources required	3
Scaffolding or crane required for wall assembly	2
Scaffolding and crane required for wall assembly	1

Question 6.5: Cost per R-value	Score
The materials cost less per R-value than a common practice wall	3
The materials cost the same per R-value as a common practice wall	2
The materials cost more per R-value than a common practice wall	1