

Expanding Markets and Industrial Practices for Thermally Modified Wood
Juan Jose Gonzalez Cordoba

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Henry J. Quesada, Co-Chair
Brian Bond, Co-Chair
Kimberly Ellis

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ABSTRACT

Thermally modified wood (TMW) contains no toxic components and is recommended for its durability, levels of equilibrium of moisture content, and dimensional stability performance. A limitation of TMW is the lack of market acceptance and products due to insufficient information regarding the performance of commercially available products. The goal of this project was to improve the market penetration and industrial processes of TMW. The first objective was to study the perception of TMW products from architects in North America using a survey instrument. Results revealed that information regarding TMW is not reaching the audience for TMW, and that providing knowledge regarding technical and marketing aspects of TMW is essential to increase the market share. The second objective consisted of the evaluation of the variability of the physical and mechanical properties of three thermally treated species manufactured in North America. Results showed that the performance of the commercially produced material was similar among the three companies, where only in seven out of 24 properties had statistical differences. Properties that were significantly different, did not have large enough differences in means to be realistically noticed by customers and all were highly different from untreated wood. The final objective involved the implementation of Lean thinking to the manufacturing process of TMW with the goal of improving the process with a direct impact on cost and waste reductions. Three companies were used as case studies for the production process. The implementation of Lean thinking in the process proposed a reduction in lead times from 55.47 days to 23.20 days, with an increase in value-added activities from 1% to 6%. Most of these gains were obtained through a reduction in inventory levels.

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PUBLIC ABSTRACT

Thermally modified wood (TMW) contains no toxic components and is recommended for its durability, levels of equilibrium of moisture content, and dimensional stability performance. The current market for TMW encounters a lack market acceptance, due to insufficient information and performance measures. The main goal of this study was to increase market penetration and study the industrial processes for manufacturing TMW, using three specific objectives.

For the first objective, a survey was conducted to study the perception of TMW among architects. The results showed that there was a lack of information regarding the technical and marketing aspects of TMW products, which needs to be addressed by distributors and producers.

The second objective consisted of the evaluation of the variability of mechanical and physical properties of three thermally treated species manufactured in North America. The results showed that the performance from the commercial processes were similar, where only seven out of 24 cases showed statistical differences based on the Analysis of Variance (ANOVA).

The final objective consisted of a Lean process strategy to produce TMW, improving the process with a direct impact on cost and waste reduction. To study the production process, three case study companies were used. The proposed Lean process reduced the lead times and value-added activities increased. The primary gain was seen in reducing inventory levels.

Dedication

I dedicate this thesis to my mother Sonia Cordoba Moya, for all her support, love and patience.

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1 Introduction

1.1 Overview

Although the United States hardwood lumber market has decreased in the past 20 years, especially since the great recession in 2009, there has been an emergence of innovative products that have caught the attention of manufacturers (Buehlmann et al. 2010 and Quesada et al., 2006). One of the innovative products that has brought attention to the U.S. lumber market and producers is thermally modified wood (TMW), which has a large variety of exterior and interior uses including; musical instruments, guns stocks, decking applications, outdoor and indoor furniture, siding, roofing, door and window frames, and flooring . Thermally modified wood has been available since the early 1990s in Europe, where it was developed as an alternative to tropical hardwoods and preservative treated wood for exterior applications. Tropical hardwoods are in high demand for furniture applications, with inelastic prices (Odoom, 2001), and are an alternative to chemically treated wood, which is attractive, due to regulations to reduce the use of toxic substances. Thermally modified wood products provide opportunities for the use of low-value timber due to increased performance against biological organisms and dimensional stability, potentially increasing the value of public and private lands with low-value wood (lower value species, quality, size), (Baynes et al., 2014).

There is a variety of information on the Internet, and in magazines and publications regarding the performance of TMW, and there is a low level of awareness from architects and consumers regarding the performance advantages and disadvantages of TMW, as well as product availability (Espinoza et al., 2015). For example, architects, who specify materials, might ask; How does TMW typically perform relative to tropical hardwoods? How expensive is TMW product compared to similar lumber products? Does TMW use any preservatives that could be hazardous to the environment? Thermally modified wood is a relatively new product

in the U.S., therefore, consumers such as architects are still hesitant to use it (Wardell 2015).

While there is some market hesitation about the use of TMW, interest has been increasing. For example, Boonstra (2008) suggested that the increased demand for sustainable building materials, and increased regulations regarding the use of toxic chemicals, has resulted in a growing interest in thermal treatments for wood. Apart from being an environmentally friendly material, benefits like increased dimensional stability, less cupping, and less warping (Aro et al. 2014) make this product attractive for a variety of exterior and interior uses.

Thermal modification is a great option to increase the physical performance of wood, such as the durability against fungi, which is increased due to the degradation of hemicelluloses like sugars (Alen et al., 2012; Wardell, 2015). Thermally modified wood products such as decking are competitively priced, when compared to traditional premium decking or tropical species such as Ipe. However, the current market for TMW in the U.S. is still hesitant to try this product, which was seen in respondents from a study conducted by Gamache (2017), where more than three-fifths of professional users of decking materials were not familiar with TMW products. Potential consumers still know little about the advantages and disadvantages of TMW, and there is an additional concern about the possible decrease in mechanical strength (Wang et al. 2012). Although there is some general knowledge that TMW could be more resistant to water absorption and have an increased resistance to decay, there is still no national or international consensus on TMW standards (Sandberg et al., 2016 and Schnabel et al., 2007). The development of standards provides safety and reliability, raising the users' confidence, which typically leads to market share expansion.

The mechanical and physical properties of TMW tend to vary based on the schedule used for modification. These schedules are the combination of treatment temperature and time of the treatment, which are different for each specie (Esteves

et al.,2008A). Thermally modified wood can be produced using a closed or open drying system. An open system is when the moisture content in the chamber goes to 0% and then the system reinjects steam to condition the wood to a 2% moisture content. A closed system maintains the centrifuge and steam in the chamber, creating additional pressure in the chamber (Ghiassi et al., 2018). During the thermal process, heat removes organic compounds and changes the cellular structure, limiting the ability of the wood to absorb water (Sandberg et al., 2016).

Performance metrics such as splitting, equilibrium moisture content (EMC), shrinkage and swelling, and water absorption show decreasing trends depending on the level of treatment (temperature levels and exposure times). Other properties such as durability, surface hardness, bending, and modulus of elasticity increased with certain levels of treatment but decreased with others (Esteves et al.,2008A).

Thermally modified wood is considered a durable exterior product (Freed et al., 2017). One of the main characteristics of TMW is the removal of moisture from the wood structure, increasing the crystalline regions in the cellulose, and increasing the percentage of lignin without replacing water with other chemicals. In addition to being chemical-free with a profound environmental impact affecting the biodegradation of wood products, TMW is lighter than standard chemically treated products. This is beneficial, because of the lack of chemical components which are being restricted by municipalities. However, TMW is not recommended for ground contact because it does not entirely remove sugars that can be consumed by fungi or insects, and testing indicates that it does not achieve the rating for ground contact. In terms of appearance, the long gradual heat process creates permanent reactions changing the color of the wood from light to a deep chocolate brown. In many cases, the new color is desirable in many potential markets (Freed et al., 2017).

There are approximately 17 producers and distributors of TMW in North America, and by 2012 the production of TMW, reported by The Forest Products Annual Market, was 100,000 m³ (UNECE/FAO, 2013). Producers of TMW believe the

market is still growing and has not yet reached peak production volumes per year. Once the awareness of the product increases and more product information becomes available, there should be significant growth. This hypothesis is supported by Huang, 2011, who suggested that a lack of product information and knowledge impact consumers who usually use product awareness to make a purchasing decision. When consumers try to find specifications of different TMW species to compare with traditional treated or non-treated wood products, they are unable to do so, due to the lack of information and available standards.

Thermally modified wood producers are in the process of trying to determine the best marketing strategies to increase the market share of this material. For many TMW producers, including the partners in this project, there is a lack of information regarding what the barriers are to expanding TMW markets and what drivers could help increase the consumption of TMW products in North America.

Not only is there a lack of standards for the product, but there is also a lack of standardization for the production process of TMW. According to the partners of the project, they are experimenting with the TMW process to get the best product that they can. The fact that this kind of wood modification technique is new in the U.S. provides opportunity for improvements in the product and the process.

One method that could be used to assist the TMW industry in improving their process is the application of Lean thinking. Lean thinking is a business model that helps managers identify waste in the value streams of manufacturing, supply chain, and services processes. Besides the presence of waste, long lead times and high manufacturing costs are also part of the main concerns in the manufacturing of TMW (Quesada et al., 2011). Lean thinking could be used to identify current problems affecting the manufacturing process of TMW and provide suggestions for improvements.

By designing an improved process strategy, manufacturing standards could eventually be implemented. This design would help create a new perception of the TMW industry, and allow consumers of the product to study and understand why TMW is a suitable choice for their projects.

The goal of this study is to increase the market size of TMW produced from low-value hardwood species, by increasing the primary customer's knowledge and acceptance of the material, while increasing the efficiency of producers.

2 Literature Review

2.1 Classification of Trees.

According to the Wood Handbook (1999), trees can be divided into two classes, hardwood and softwood. These names are confusing because some softwoods have a harder texture and some hardwoods have softer wood. Softwoods are gymnosperms or conifers, with nonporous needle leaves that maintain the majority of their leaves in the winter.

Hardwoods are all those trees with broad leaves. Botanically, they are angiosperms and their seeds are enclosed in the ovary of the flower. Anatomically, hardwoods are porous and contain vessel elements. (Ross, 2010). The structural complexity in hardwoods is greater than in softwoods because they have both a higher number of primary cell types and a far greater degree of cell types (Ross, 2010).

2.1.1 Hardwood Lumber

Based on *An Analysis of the Timber Situation in the United States: 1952 to 2050* and *The 2005 RPA timber Assessment Update*, there are more than 100 wood species. Sixty percent of them are of primary commercial importance. In Figure 1 the species are displayed along with their locations.

Western	Northern and Appalachian	Southern
Hardwoods		
Alder, red	Ash	Ash
Ash, Oregon	Aspen	Basswood
Aspen	Basswood	Beech
Birch, paper	Beech	Butternut
Cottonwood	Birch	Cottonwood
Maple, bigleaf	Buckeye	Elm
Oak, California black	Butternut	Hackberry
Oak, Oregon white	Cherry	Hickory
Tanoak	Cottonwood	Honeylocust
	Elm	Locust, black
	Hackberry	Magnolia
	Hickory	Maple, soft
	Honeylocust	Oak, red and white
	Locust, black	Sassafras
	Maple, hard	Sweetgum
	Maple, soft	Sycamore
	Oak, red and white	Tupelo
	Sycamore	Walnut
	Walnut	Willow
	Yellow-poplar	Yellow-poplar
	Cedar, northern white	Baldcypress
	Fir, balsam	Cedar, Atlantic white
	Hemlock, eastern	Fir, Fraser
	Pine, eastern white	Pine, southern
	Pine, Jack	Redcedar, eastern
	Pine, red	
	Redcedar, eastern	
	Spruce, eastern	
	Tamarack	

Source: Wood Handbook, Ross (2010)

Figure 1 Hardwood Species.

This project proposes to increase the consumption of TMW made from low-value hardwood species that are abundant in national forest systems and other forest lands in the eastern United States. Pulpwood markets continue to decrease in the Appalachian region due to low demand from paper mills and logging. Harvesting companies are struggling to find markets for low-value hardwood species such as red maple (*A. rubrum*) and white ash (*Fraxinus americana*), which are the most abundant hardwood species, after yellow poplar (*Liriodendron tulipifera*), and oak in eastern forests. Some of the characteristics, according to the Wood Handbook, are displayed in Table 1.

Table 1. Characteristics and uses of sweetgum, yellow poplar, and red maple.

Specie	Characteristics	Uses
Ash	Heavy Strong Stiff Hard	Doors Flooring Furniture Joinery
Yellow Poplar	Moderately light in weight Moderately low in bending strength Moderately soft Moderately high shrinkage	Furniture Interior molding Siding Cabinets
Red Maple	Moderately hard Moderately strong Moderately heavy	Pallets Furniture Veneer

Source: Wood Handbook, Ross (2010)

2.1.2 Hardwood Industry and Markets

The estimated domestic hardwood lumber consumption and export grew by 20% and 34%, respectively, from 1991 to 1999, reaching their peak in 1999 and then started to decline, after apparently augmenting domestic production with imported furniture. The U.S. furniture industry started to move offshore at the beginning of 2000. (Luppold et al., 2016B). According to Luppold et al., (2016B), one of the largest sectors that affected hardwood markets in the United States was the housing industry, and when this sector declined, the market for decorative wood also decreased. Since hardwood lumber is not often used in construction in the United States, engineering and innovation have developed building materials such as structural frames and floors (D. la Roche et al., 2003; Hurmekoski, et, al, 2015). The hardwood industry started to see substantial growth in the furniture market in the 1970's, followed by the export market, which also had an impact on the hardwood industry (Luppold et al., 2016A). By the beginning of the 2000's, the export market reached its climax in the United States, when the U.S. was the largest exporter of hardwood in the world. During the great recession, the exports fluctuated but were

still strong, compared to domestic hardwood lumber consumption which saw a decline of 43% from 1999 levels (Luppold et al., 2011).

United States hardwood lumber exports doubled from 2009 to 2014, as shown in Table 2, with 2017 being higher than the record year of 2014. China has been the driving force in the import of the U.S. hardwood lumber. China's growth increased from 16% in 2007 to 57% in 2017.

Table 2. Key Customers for US Hardwood Lumber Exports from 2007 to 2017.

Year	Canada	China	Mexico	Italy	Vietnam	Total, to world
2007	370	222	98	111	65	1422
2008	305	187	83	81	60	1131
2009	200	209	68	69	60	921
2010	266	359	83	109	101	1322
2011	242	508	82	76	99	1443
2012	258	603	89	56	131	1593
2013	263	813	110	57	155	1859
2014	299	1096	126	56	185	2336
2015	249	965	115	43	155	2060
2016	247	1195	117	38	157	2262
2017	259	1511	114	42	192	2647
2018	262	1313	110	39	224	2495
2019	247	760	117	32	225	1883

Source: USDA, Foreign Agricultural Service.

Given the reduction for demand of hardwoods produced in the United States, producers began to look for new markets. In a survey conducted by Buehlmann, he acknowledged, "*Hardwood lumber distributors indicated that their future success depends on offering a wider product range, offering environmentally friendly/certified products, filling smaller and more exacting orders, and faster service.*" (Buehlmann, et, al, 2010). With the emergence of regulations limiting the use of toxic chemical treatments, these "environmentally friendly/certified products" are an alternative that could be attractive in the 21st century to the U.S. market (Hill, 2011). This idea was also highlighted by Dasmohapatra (2009), that wood products would be affected by innovation, where one of the most impactful drivers would be the use of

environmentally friendly products. Working with renewable natural resources will help the market give valued-added opportunities, due to the expanding global demand for products with a small environmental footprint. There are several types of wood modifications that meet these criteria and increase the value and performance of wood without harming the environment, leading to market opportunities for different applications such as flooring, siding, framing, and interior and exterior uses.

Wood modification is an alternative that protects wood, without using toxic chemicals, by physically altering the wood structure chemically (Hill, 2007). There are several types of wood modification. A few examples of commercial wood modifications are Acetylation wood, Furfurylation wood, Thermosetting resins, 1.3-dimethylol-4.5-dihydroxyethyleneurea (DMDHEU) and TMW.

2.1.3 Type of Modifications

Several wood treatments can be used to protect wood and have been used in the industry for a long time, such as non-biocidal, chemical, or thermal treatments (Evans, 2003). Non-biocidal treatments use natural extracts for wood preservatives, such as acetylation that increases the durability of wood (Binbuga et al., 2009; Vetter et al., (2013); Mohebbi et al., (2010) and Rowell (2006)). Chemical treatments involve the use of chemicals which bond with the wood cell wall polymers to improve durability, water absorption, stability, and mechanical properties (Popescu et al., (2019). The next section briefly introduces these common modification processes.

2.1.3.1 Acetylated Wood

The acetylated wood modification was developed in Germany by Fuchs (1928). This modification initially used anhydride and sulfuric acid as a catalyst to accelerate the modification process. Most of the producers do not currently use a catalyst on their process, and the process is only done using acetic anhydride (Larsson-Brelid 2013; Rowell 2016; Mantanis 2017).

Several authors reported on the performance of acetylated wood, showing that the performance of both swelling and shrinkage properties were reduced by 70% - 80%, as compared to untreated wood values, and the hardness values increased from 15% to 30%. Additionally, the wood showed an increased biological resistance to brown-rot and white-rot fungi, increasing its durability to the highest class (Class 1), extremely durable (Larsson-Brelid et al., 2013; Rowell, 2016; Jones et al., 2007). This treatment also made the wood resistant to subterranean and Formosan termites (Alexander et al., 2014).

According to Sandberg (2017), a company in The Netherlands produces acetylated wood under the commercial name Accoya® with radiata pine (*Pinus radiata*) and alder (*Alnus spp*). Rowell (2016) reported that most of the applications for acetylated wood are for exterior windows and doors, decking, and cladding. However, Mantanis (2017) reported that this modification was limited to only alder (*Alnus spp.*) and radiata pine (*Pinus radiata*) due to the producers only working with these species and a lack of product availability. Another barrier for this modification is that the production costs involved are high which caused the commercialization of the product in the U.S. to fail (Rowell 2016).

2.1.3.2 Furfurylated Wood

The implementation of furfuryl alcohol (FA) was proposed by Dr. Alfred Stamm in 1950 to improve physical and biological properties like the reduction of moisture content and decay (Lande et al., 2008). According to Lande et al. (2004), the industrial process of furfurylated wood starts with the mixing of chemicals (furfuryl alcohol, initiators/catalysts, buffering agents, surfactants, and water) and then the solution is pumped to buffer tanks. Once the solution is ready, the wood is impregnated using vacuum pressure, and then heated in a chamber injected with steam. When the wood material comes out of the chamber there is a final drying to minimize emissions and obtain a desirable final moisture content.

The mechanical and physical properties of furfurylated wood are greatly improved. According to several authors, the biological durability of the furfurylated wood is

considered a “Class 1”, meaning that it is exceptionally durable. Results obtained from Gerardin (2016), showed decay resistance over a period of nine years with moderate loading of furfuryl (30-35% of weight percentage gain). The hardness performance showed improved values when compared to untreated lumber, although it is still more brittle, since a drawback is decreased impact bending with a modest reduction of impact strength (Larsson-Brelid, 2013; Lande et al., 2008)). The dimensional stability and resistance to weathering are 50% lower than untreated wood.

Furfurylated wood is produced by Kenoby A.S, located in Norway, Sandberg (2017). Kenoby A.S produces two different Furfurylated wood products: Kebony Clear® and Kebony Character®. Kebony Clear® is used with radiata pine, southern yellow pine, and maple, and its main application is flooring. Kebony Character® is used mainly in decking, siding, roofing, and outdoor furniture with Scots pine wood. The difference is that Kebony Clear® is highly loaded with furfuryl and Kenoby Character® is more lightly loaded with furfuryl.

2.1.3.3 Thermosetting Resins Modifications

During the 1940s, A. Stamm experimented with impregnation modification using formaldehyde-based resins. One of the first projects included the impregnation of wood with phenol-formaldehyde resins, which improved the durability against fungi, termites, and marine borers, and also improved the dimensional stability (ASE) by 58% (Sandberg et al., 2016; Stamm and Seborg, 2015). By 1955, Stamm added heat and compression to wood products alongside phenol-formaldehyde, which lead to the creation of Compreg® and Impreg®. Products from Compreg® are known to have good mechanical properties, such as hardness, abrasion resistance, and high compression strength, although there are no values reported (Hill, 2007; Sandberg et al., 2016).

Another resin used for impregnation of wood is melamine-formaldehyde, where the modified wood shows high resistance to fungi attack and increased dimensional

stability but has high production costs. Another drawback is that under humid-dry cycle conditions the wood products tend to crack (Inoue et al. 1993).

2.1.3.4 DMDHEU Modification

This modification involves the use of highly porous species such as pine, which is impregnated with 1,3-dimethylol-4,5-dihydroxyethyleneurea (DMDHEU) under high pressure conditions. This reagent comes from the textile industry and it has an anti-shrinkage efficiency (ASE) of 75%. Normally, with a treatment, authors have reported ASE values between 30-40% (Krause and Militz, 2009;). DMDHEU durability showed weight loss values between 1-3% (Kurt et al., 2018; Nicholas et al., 1987).

The industrial process consists of several stages. The first stage is penetrating the wood material with a solution of DMDHEU (Militz, 2002). Then a vacuum is applied so the solution can reach the innermost cells under pressure. Then the wood material is impregnated at a slow rate at a temperature of 100-120 °C under humid conditions, causing the agent molecules to cure by polycondensation after the water is released (Krause et al., 2003). Currently, the modification process is produced in Germany under the Belmadur® trademark. The major drawbacks are brittleness, the high emissions of formaldehyde from the product, as well as a tendency to crack (Sandberg, 2016). Key applications are decking, exterior windows, and garden furniture.

2.1.3.5 Chemical Modification

Chemical modification was first done by Tarkow in 1945 and it is defined as covalently bonding a chemical group to reactive parts of the cell wall polymers. Rowell (2005) reported that there are many chemical reaction systems with chemicals such as acid chlorides, carboxylic acids, isocyanates, formaldehyde, methylation, and more with the goal of improving dimensional stability and resistance to biological degradation. The antishrinkage efficiency of chemically modified solid pine with Propylene Oxide, Butylene Oxide, Acetic Anhydride, or Methyl Isocyanate was reported at 62% – 74%. Since the moisture content is reduced due to chemical

modification, the biological resistance increases. The weight loss percentage after 12 weeks against brown-rot fungus for Propylene Oxide, Butylene Oxide, Methyl Isocyanate, Acetic Anhydride and Formaldehyde was 2% to 14% and for white fungus the performance was reported between 1%-2% (Rowell, 2006). The main disadvantages of using chemicals is that they might have residual smells after the chemical reactions and are not considered cost effective for commercialization (Rowell, 2005).

2.2 Thermally Modified Wood

Thermally modified wood treatment consists of heating wood at high temperatures and pressure, resulting in the degradation of the cell walls' chemical components (Čermák et al., 2016). Thermally modified wood consists of the deformation of the lignin-polysaccharide due to the organic acids from hemicellulose (LeVan et al., 1990; Zaman et al., 2000). The lignin-polysaccharide consists of a mixture of cellulose, hemicelluloses, and lignin (Bi et al., 2016). Additionally, the lignin-polysaccharide is part of cell walls and is the most abundant biological material on earth (Fernando et al., 2006). The process involves the decomposition of the hemicelluloses when the temperature reaches 180-200 C, making the molecular configurations less amenable to a reaction with water, and also decreasing the hydroxyl groups (Esteves et al., 2008A; Weiland et al., 2003; González et al., 2009).

The hydroxyl groups are responsible for the absorption of moisture, are related to dimensional stability, and allow for biological attack of the wood (Hill, 2007). When the cell walls do not absorb as much water, due to the decrease of the hydroxyl groups, the equilibrium moisture content (EMC) also decreases. The reduction of the EMC has been shown to decrease swelling and shrinking of wood; this is the basis for all heat treatment processes (Esteves et al., 2008A). On average, the EMC decreases by about half, compared to untreated wood (Sandberg and Kutnar, 2016). The decrease of the hydroxyl groups also increases the dimensional stability of the material. Heat treatment causes improvements in durability and resistance to rot, weathering, and insects. It also causes the color to change to darker tones (Esteves

et al., 2008A). However, TMW tends to show a decrease in mechanical strength, impact resistance, and abrasion resistance (Hill, 2007). Lastly, two of the properties most affected by heat treatments are the MOE and MOR, the modulus of elasticity and modulus of rupture. The MOE represents how much the material can bend and recover its initial form without damaging its structure, while the MOR is a criterion of strength, reflecting the maximum capacity of load that the material can resist just before it ruptures. Studies have shown that the MOE tends to increase in softer treatments and decrease in harder treatments; it is considered a softer or harder treatment depending on temperature and time exposure in the modification. As for MOR, a significant decrease is observed when the heat is applied using different processes of thermal modification (Esteves et al., 2008A; Hill, 2007; Sanberg and Kutnar, 2016; Wood Handbook, 2010).

The anatomical effect of TMW differs depending on the treatment conditions and wood species (Boonstra et al., 2006). According to Fengel et al. (1989), treating spruce wood at 150°C, they observed some cracks in the cell corners, and the outer and middle layers of the cell wall structure. Spruce wood, with a thermal treatment between 180 and 200°C, resulted in cracks in the outer layer and the middle lamella of the cell wall structure (Fengel, 1966). Gosselink et al. (2004) observed that Scots pine at 275°C for 15 minutes resulted in an increased size and number of pores in the wood structure. Some species, such as *Grevillea Robusta*, under heat treatment, does not present any anatomical structure changes in vessels, fibers, parenchyma, or rays (Mburu et al., 2007).

2.2.1 Characteristics of Thermal Modification

Wood is one of the oldest construction materials used by humans. It is a well-known material because it is natural and renewable. When a thermal modification is chosen to improve wood performance, not only is the industry already working with non-toxic material, but a green modification method is used. This process does not require more variables than water, heat, pressure and in some cases, mechanical force.

Furthermore, thermal modification uses relatively small amounts of energy (Navi and Sandberg, 2012). Espinoza et al. (2015) state that the use of chemicals in wood modification creates a growing concern since it affects the environment negatively. Thermal modification appears to be a potential substitute for chemical treatments.

Moreover, the product obtained through this modification process has vibrant color and enhanced durability, among other characteristics, making it a reliable competition for tropical wood species. Over the past years, the U.S. import of tropical wood has increased due to customers demanding this product for its exceptional application in furniture and exterior design, as well as aesthetics. In 2006, the value for tropical timber imports, excluding furniture, was nearly \$1.6 billion (Bandara et al., 2012). The same applications are possible with TMW as with tropical wood, which represents an opportunity to reduce the consumption of imported products by replacing them with domestically produced materials (ITTO,2012).

2.2.2 Status of Thermally Modified Wood Market in the US

Thermally modified wood products have been available in the United States since 2004 when Westwood Corp started exhibiting thermally-treated wood products at fairs, and companies such as Jartek Inc. and Stellac Inc also started exhibiting TMW products (Sandberg et al., 2015). By 2012, Canada and the United States had seven and ten manufacturers of TMW, respectively.

Sandberg (2015) reported that the production of TMW products was intended as an alternative option to chromate copper arsenate treatments, due to the toxic components the treatment had. The use of treated wood in children's playgrounds and finishing products was being restricted in the United States due to toxicity. With the emerging regulations, many companies started to incorporate the production of TMW products. The lack of toxic substances that TMW provides make it suitable for a variety of applications.

Espinoza (2015) studied the marketing strategies, barriers, and drivers from the perspective of TMW producers and distributors in the U.S. and found that most of

the applications for TMW were for furniture, decking, siding, and flooring, where they were ideal for products that increased durability and stability performances. Additionally, most of the participants worked directly with architects and awareness of TMW was growing among them.

The adoption of TMW has had limited success according to Donahue (2014), which is showcased by the low production levels reported by the United Nations Economic Commission for Europe (UNECE) and the Food and Agriculture Organization (FAO) (2013) in the Forest Products Annual Market review, that the volume production of TMW between 2012 and 2013 was around 315,000 m³ in Europe and 100,000 m³ in the United States. This was also the last report from the Forest Products Annual Market review containing this information, since consumers and producers were hesitant to provide updated information.

The study conducted by Espinoza (2015) also expressed the lack of standards as a significant concern for TMW producers. As of 2019, there were no recognized standards for testing TMW. Europe has technical specifications for Spruce and Pine as shown in “DS/CEN/TS 15679 Thermally Modified Timber – Definitions and Characteristics”. Additionally, in Europe TMW has a certificate for “Quality Mark TMT”, certifying that the product conforms to the requirements of EN ISO/IEC 17067, which is specified by wood species, occasionally grading, manufacturers, and types of treatments. It is also certified with the “DIN 68800 Wood Preservation”. (CEN, 2007; EPH, 2015 and DIN, 2011). Most of the research done on mechanical properties and physical properties have been conducted using the ASTM and AWWA standards (Schneid et al., 2014; Kocaefe et al., 2008; Shi et al., 2007).

2.2.2.1 Export Markets

The export markets for TMW consist of a mix of customers from different regions of the world. The only study on export markets from the United States was conducted by Espinoza (2015) and had a sample size of 16 different companies. The primary export markets for the respondents were Japan, China, Germany, Italy, Spain, Russia, Ukraine, India, Taiwan, West Africa, France, Portugal, Vietnam, Philippines,

Belgium, Turkey, India, Australia, New Zealand, and Israel. The variety of northern hardwood species used by the companies were ash, yellow poplar, maple, cherry, soft maple, red oak, red pine, white pine, and sweet maple. The companies reported that 50% of their production was exported, showing how attractive the United States TMW products are to international market.

2.2.3 Thermally Modified Wood Commercial Processes

Practices for TMW have been around since 1920, when wood was exposed to high temperatures inducing a decrease in the equilibrium moisture (Tiemann, 1920). Throughout the years, several treatments have been developed with different process conditions, using temperatures between 160° and 260°C, depending on wood species, and the intended use for the final product. The main products are Thermowood (Finland), Platowood (Holland), OHT-Oil Heat Treatment (Germany), Bois Perdure and Rectification both from France (Militz, 2012).

Thermowood is produced using a treatment in a humid atmosphere for two to ten hours at temperatures above 150°C, until the wood reaches a mass loss of 3% (Esteves et al., 2008A). According to Syrjänen et al., (2000), the treatments to achieve the desired conditions must be made with steam, with no more than 3% to 5% oxygen, must not have pressure, and with an airspeed of at least 10 m/s. The Thermowood process was developed in Europe and, according to Esteves (2009), is the most successful in Europe, and the technology is now also being used in Canada (Shi et al. 2007).

The Plato Wood process works with green wood, and has three steps. The first step consists of an initial heat treatment for 4 to 5 hours at 160°C to 190°C, with a pressure higher than the atmospheric pressure, and humid conditions (Boonstra et al. 1998). Then the wood must be dried until it reaches 10% of the equilibrium moisture. The wood is then heated to 170°C to 190°C for 14 to 16 hours but this time in dry conditions (Militz, 2002).

The Rectification heat treatment works in a chamber with temperatures from 200°C

to 240°C using nitrogen, with low levels of oxygen, using wood with 12% moisture (Esteves et al., 2008A). The Bois Perdure treatment uses greenwood, which is dried by vapor and combustion gases, and later is re-injected in a combustion chamber at temperatures between 200°C and 240°C. (Esteves et al., 2008A).

The TERMOVUOTO process is an alternative for thermal modification using a vacuum to reduce the oxygen inside the reactor, while volatiles and water vapor are removed using a vacuum pump (Sandberg, 2017). According to Candelier (2014), the thermo-vacuum system does not severely affect the mechanical properties of lumber, compared to other processes. This process is currently in use by two of the partners of this project.

The thermo-hydro treatment uses an autoclave to heat wood using high-pressure superheated steam (hydrothermolysis), and is then dried in a kiln (Stamm 1956; Burmester 1973; Giebeler 1983; Ruyter 1989; Boonstra et al., 1998; Tjeerdsma et al., 1998; Willems 2009). The final phase of this treatment consists of curing the wood at 170-190°C (Tjeerdsma et al., 1998). This treatment is like the Plato-Process, the difference being that this treatment involves different steps (hydrothermolysis, drying, and partial curing) using a single piece of equipment (autoclave) (Biziks, 2015).

The oil heat treatment OHT is a wood treatment, which uses oil at high temperatures. The oil is introduced in a closed vessel with green wood. The process has two phases. The first phase is a heating process that takes approximately two to four hours and 14 hours for a cooling phase; for a total of 18 hours (Esteves et al., 2008A). Working with oil on woods increases the mass to around 50-70% and the oxygen is limited (Sailer et al., 2000, Rapp et al., 2001). According to Lee et al., (2018), the OHT treatment is suitable for flooring and outdoor applications such as fencing, garden furniture, and cladding.

The mechanical and physical performance of two softwood species treated with different commercial processes was tested by Jebrane et al., (2018) using Norway spruce and Scots pine. The samples were treated under industrial conditions with

steam (Thermowood®) and vacuum (Thermovouto). The results showed that the lumber treated with vacuum had lighter color than the lumber using steam, and, in general, the mechanical and physical properties and durability had similar results for each commercial process studied.

The next section discusses in more depth the mechanical and physical performance of TMW from different studies with different species, temperatures, and exposure times.

2.2.4 Mechanical Performance

The thermal modification of wood has long been recognized as a potentially useful method to improve the dimensional stabilization of wood and increase its decay resistance (Hill, 2007). However, thermal treatments can also impact MOE, MOR hardness, color, and odor.

According to Hill (2007), when wood is submitted to heat treatments the molecular composition is altered, improving some mechanical properties such as dimensional stability. However, this can vary depending on the conditions of the treatment. The hardness only improves at the beginning of the heating process, but eventually decreases.

This project evaluates how TMW performs against static bending (MOE/MOR) and hardness.

2.2.4.1 Static Bending – Modulus of Elasticity

The modulus of elasticity, usually called the Young's modulus, can be estimated using a tension or compression test and is commonly measured using ASTM D-143. Esteves (2009) mentions that this mechanical property is affected by the period of the treatment, where there is an increase in MOE when wood is thermally treated for short periods. Inoue et al. (1993), working with *Cryptomeria Japonica* determined that wood initially presented a small increase in MOE and started decreasing by

10% at temperatures of 180°C for 20 hours, and at 220°C for eight hours it had a significant reduction of 60%. Rusche (1973) studied the behavior of beech and pine using different schedules. He found a relation between the decrease in strength and work to maximum load in the function of the mass loss, without consideration of the treatment and species. The reduction in MOE only became significant when the mass loss exceeded 8%. Having low MOE values would have an influence on applications like decking, since MOE is the resistance to deformation under the load of a given beam.

North American species such as pine, sweetgum and red oak were treated by Adewopo (2011) at temperatures of 149°C and 204°C for two to eight hours. The MOE results showed values for pine between 13,300 MPa to 14,280 MPa. For sweetgum, the MOE performance was between 13,670 to 14,820 MPa, and the performance for red oak it was between 20,670 MPa to 21,980 MPa.

On a study conducted by Donahue (2011) he tested the MOE performance of TM yellow poplar and obtained MOE values between 96.77 MPa to 96.62 MPa and had an incremental performance compared to untreated samples with values of 103 MPa.

2.2.4.2 Static Bending – Modulus of rupture

When wood is submitted to heat treatment, one of the most negatively affected mechanical properties is the maximum resistance to bending, expressed as modulus of rupture (MOR) (Esteves, 2009). The MOR measures a beam's strength before its rupture and is used to determine overall strength (Hill, 2007).

As with the MOE, the MOR is affected, depending on the species and treatment used. Inoue et al. (1993) used three treatments at conditions at 180°C, 200°C, and 220°C, on *Cryptomeria japonica* where the MOR performance decreased by 80%, 45%, and 20% respectively after eight hours of exposure.

On a study conducted by Donahue (2011) he tested the MOR performance of TM yellow poplar and obtained MOR values between 11,734 MPa to 12,258 MPa and had an incremental performance compared to untreated samples with values of 11,100 MPa

2.2.4.3 Hardness

Hardness is the resistance of a given material to indentation using a modified Janka hardness test that measures the force required to embed a ball to one-half of its diameter (Hill, 2007).

One of the applications of thermally modified lumber is flooring, where it is necessary to utilize products with high hardness values (Leitch, 2009). The impact of thermal modification on the hardness of wood is mixed. Some research shows a decrease in hardness and others show an increase. For example, Bakar et al. (2012) studied the hardness performance of thermally modified red oak, eastern red cedar, and rubberwood, exposing the wood at 120°C and 190°C for two and eight hours. The test was done perpendicular to the grain direction, and despite the four different conditions used in the study, the average performance showed a 33% decrease on hardness for each specie evaluated. Similar results were obtained from Korkut (2008) with red maple, where he studied modified wood at 120°C, 150°C, and 180°C for two, six, and ten hours. The maximum loss was from samples treated at 180°C for ten hours; showing cross-section 31%, radial 54% and tangential 51%.

The treatment with a higher temperature and time exposure had the worst-performing results. However, Boonstra (2007) reported different results with radiata pine, Scots pine, and Norway spruce that showed a slight hardness increase in the perpendicular hardness and a significant increase parallel to the grain by 5% and 48% respectively. These results highlight that the hardness performance will likely be dependent on the treatment conditions and species treated, since there is a clear differentiation between softwood and hardwood species.

2.2.5 Physical Performance

2.2.5.1 Equilibrium of Moisture Content

A reduction in equilibrium of moisture content (EMC) always occurs with thermal modification, because the process dries the wood at high temperatures (Tiemann, 1920). The EMC is affected since the ability to bind water throughout wood is reduced due to the chemical modification of the cell wall, with the reduction in hemicellulose and fewer hydroxyl groups (Li et al., 2011; Sundqvist, 2002; Brischke et al., 2007). The advantages of lowering the EMC values, and thermally modified wood products with low EMC values, is that the environment temperature and relative humidity change over the seasons, resulting in absorbing and releasing moisture to adjust to the new EMC. While wood is adjusting to the EMC, it will start to warp, crack, and split (Simpson, 1998). Esteves (2009) reported multiple variables that affect the moisture content such as species, temperature, time, and type of treatment, making this difficult to compare with the EMC performance from different authors.

Calonego et al. (2012) studied the physical and mechanical properties of heat-treated wood with *Eucalyptus grandis* at conditions of 140°C, 160°C, 180°C, 200°C, and 220°C. The samples reported approximately 9% to 5% moisture at equilibrium, where the higher the conditions of the heat treatment, the lower the equilibrium of moisture content of the specimens. Similar results were shown in a study developed by Brito et al. (2018) when she studied the durability of yellow poplar against fungi. The untreated samples averaged 10%, and with higher treatment conditions the EMC would decrease when the conditions were 21°C and 65% RH. Overall, the EMC performance of TMW is dependent, to some extent, on the modification schedule used. The use of high temperatures to treat lumber results in a reduced EMC compared to a schedule with low temperatures (Cai, 2019).

2.2.5.2 Dimensional Stability

The dimensional stability in wood is when there are changes in the dimensions as it gains moisture (swells) or loses moisture (shrinks), due to the amount of water that can be held by the cell walls (Hill, 2007). Shrinking can result in the wood cracking, warping, and splitting, affecting applications such as flooring and siding. Shrinkage values can be measured from the tangential and radial surface when it reaches equilibrium of moisture content and after it is oven dried.

On a study conducted by Donahue (2011) he tested the dimensional stability performance of TM yellow poplar. The width values improved from 3% of shrinkage to 1% for both treatments at 200°C and 210°C. The thickness shrinkage improved from 2% to 1% for both treatments.

Dimensional stability is increased when wood is thermally modified, but the effect observed is dependent upon the heating schedules used (Hill, 2007). The increase of dimensional stability is also dependent on the plane of reference (Sailer et al., 2000, Tjeerdsma et al. 1998b). Sun et al. (2013) studied the changes in the dimensional stability of *Eucalyptus pellita* in terms of the volumetric anti-shrinking efficiency (ASE_1) and anti-swelling efficiency (ASE_2) according to the Chinese standard GB/1932-2009. Due to the decrease of the EMC on heated wood, the ASE_1 increased by 40% at 240°C for ten hours, and the ASE_2 also increased 42°C under the same conditions. Another study reported the dimensional changes as the tangential-radial shrinkage ratio on mindi (*M. azedarch* L.), mahogany (*S. macrophylla*), red oak (*Quercus falcate Michx.*), and southern pine (*P. taeda* L.) with dimensions of 40x55x19 mm³ at conditions of 130°C and 200°C. Priadi et al. (2013) results showed that the tangential-radial shrinkage ratio for the mindi, mahogany, oak, and pine were 1.1, 1.2, 1.4, and 1.9, respectively. The author expressed that the results were expected, due to the vertical orientations of the microfibrils, the tangential direction was going to be stronger than the radial.

Zivkovic et al. (2008) studied the dimensionality of heat-treated wood on ash (Jasenovina) and beech (Bukovina) with the ASE. The specimens were stored in a

conditioning chamber at 23°C and 50% relative humidity, reaching 8% MC for the beechwood and 10% MC for the ash. The study reported improvements of 27% and 35% in both beech and ash respectively, with a treatment at 190°C and with a treatment of 210°C the species presented improvements of 54% and 62%, showing that the higher the conditions of the treatments used on these species, the higher the increases in the dimensional stability.

Dimensional stability, as mentioned earlier, is key for flooring, siding, and exterior applications, where wood is exposed to moisture due to the climate changes. With TMW products increasing the shrinkage performance, they become suitable for the applications mentioned.

Some North American species were tested by Priadi (2013) to determine the dimensional stability performance of red oak, pine, mindi and mahogany. The samples were heat treated at temperatures of 130°C and 200°C for two and eight hours of exposure. Overall, the results showed that, at conditions of 200°C for a time period of two hours, a maximum reduction of the swelling value of 57% compared to untreated samples and for conditions of 200°C for eight hours, with a maximum swelling reduction value of 68%.

2.2.5.3 Durability

Durability in wood is the ability to resist biological attacks like fungus and it is a fundamental aspect to consider before using wood products (Gao et al., 2017). Durability is measured by weight loss percentage and visual rating after it is exposed to biological organisms for several weeks.

Thermally modified wood is commonly used in applications in which it is exposed to weather and humidity variations, such as flooring, panels, furniture, and more (Sandberg, 2015). In these applications, the resistance to biological organisms is fundamental to fulfill user requirements.

On a study conducted by Donahue (2011) he tested the durability performance of TM yellow. The samples were tested with two fungus, a white rot (*Trametes versicolor*) and a brown rot (*Gloeophyllum trabeum*). The durability performance with a white rot went from 35% with controlled samples and for samples treated at conditions of 200°C it had a weight loss percentage of 4% and at 210°C the weight loss was at 8%. The performance with a brown rot for untreated samples was at 28% and showed improved values for treatments at 200°C and 210°C with a weight loss percentage of 12% and 14%, respectively.

Thermal modification has shown improvement on the durability of wood. For example, Brito et al. (2018) demonstrated that when yellow poplar was thermally modified at 220°C it could improve decay resistance to white-rot fungus (*P. sanguines*) by 81%. Other studies on decay resistance with Scots pine, oak, and beech against white-rot and brown-rot demonstrated that samples treated at 190°C and 212°C, for two hours would improve its durability, as is shown in Table 3 (Ayata et al., 2017). Also, the results showed that treated wood had increased resistance to brown-rot fungi that white-rot. Similar results were obtained by Tjeerdsma et al., (2000) with *Pinus radiate*, *Pimus sylvestris*, *Pseudotsuga menziesi*, and *Picea abies*, where the resistance for both white-rot and brown-rot fungus improved; however, the best performance was seen against brown rot.

Table 3. Weigh Loss of pine, beech, oak.

Wood type	Temperature (°C)	White rot (<i>P. ostreatus</i>)		Brown rot (<i>C. puteana</i>)	
		Mean	Standard deviation	Mean	Standard deviation
Scotch Pine (<i>Pinus sylvestris</i>)	Control	23.04	1.46	25.48	10.54
	190°C for 2 h	11.66	2.75	1.9	1.04
	212°C for 1 h	8.93	5.23	0.72	0.23
	212°C for 2 h	6.74	2.28	0.1	0.72
Beech (<i>Fagus orientalis</i>)	Control	22.87	3.25	23.74	10.16
	190°C for 2 h	11.38	4.32	2.18	2.41
	212°C for 1 h	6.02	1.35	1.19	0.35
	212°C for 2 h	6.37	2.71	0.67	0.03
Oak (<i>Quercus petraeae</i>)	Control	21.54	5.07	11.2	7.57
	190°C for 2 h	8.59	4.56	3.95	1.56
	212°C for 1 h	7.58	3.33	1.67	0.85
	212°C for 2 h	4.74	2.36	0.38	0.33

Source: Ayata et al., (2017)

Wood is affected by rot when the environment has high humidity. According to (Esteves et al., 2008A), wood that has been heat treated has increased biodegradation durability. Thermally modified wood products are effective due to the thermal process that removes a high percentage of potential sugars that are a source of food for insects and fungi.

2.2.6 Treatment on Thermally Modified wood

There has been other research based on a treatment for TMW using wax emulsion (WE) and disodium octoborate tetrahydrate (DOT) showing some of the mechanical properties that usually decline from heat treatments and can be increased from WE, DOT or both (Wang et al., 2012). In previous research, the heat treatment was applied to red-bud maple, experimenting with three different temperatures for three distinct periods, resulting in decreased values of the density, swelling, and surface. (Korkut et al., 2008). An application of heat treatments on Oriented Strand Board (OSB) panels at different temperatures showed groups exposed at 200° C showed a negative effect on physical and mechanical properties. The performance of the samples was better with a treatment of 240° C, and these treatments did not maintain the dimensional stability of OSB (Mendes et al., 2013).

2.3 Lean Thinking

Lean is a term frequently used in business, when greater value for the consumer is created, while using fewer resources. When a business adopts Lean principles or Lean thinking, they try to eliminate waste and increase operational efficiency. Lean thinking refers to a process that focuses on the increase of value-added to goods and services, while reducing waste. Lean has become a universally accepted term for increasing value and reducing waste (Quesada et al., 2011). When talking about Lean thinking, there is a related concept called value chains. Companies convert raw material into goods or services that customers demand through a value chains, and it is the final consumer of these goods or services who allocates the value (Quesada et al., 2011).

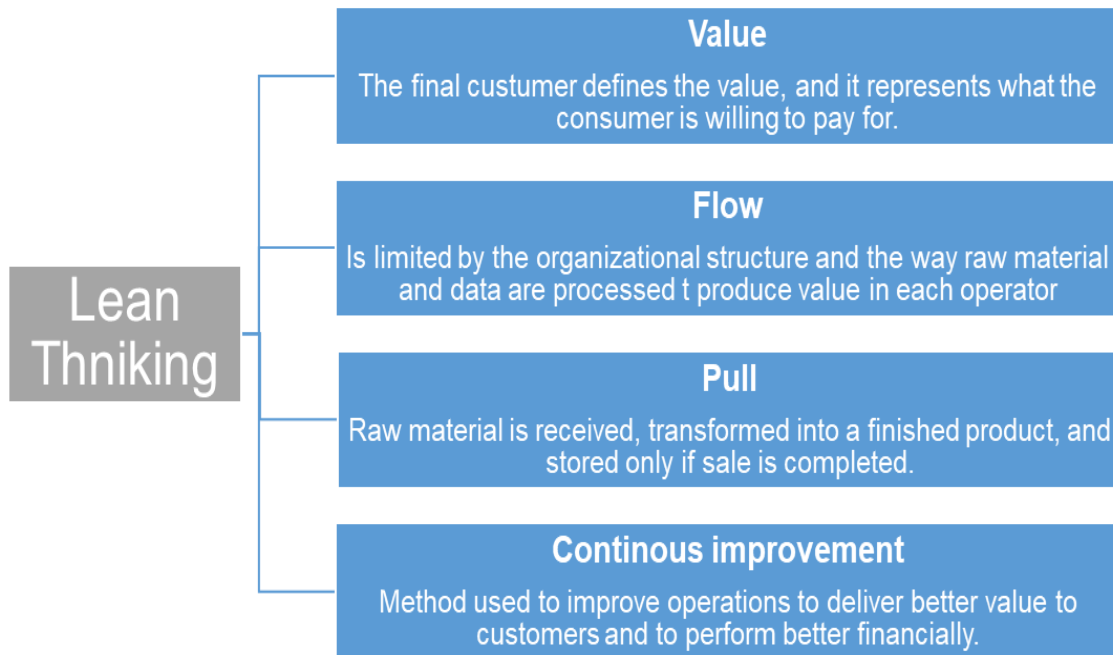
Hines (1999) referred to value-adding operations as the activities where raw materials or semi-finished products are processed through manual labor, making them more valuable to the end consumer. The customer expects all activities to be “value-adding” (VA), but in reality, some activities are non-value adding (NVA), meaning that they are wasteful actions such as setting up a chamber or machine. These operations might take seconds or minutes and are not adding value to a final product. Lean thinking considers the identification of VA and NVA operations to be fundamental. According to Womack (1991), there are seven types of waste present in processes: overproduction, waiting, unnecessary transportation, over processing, excess inventories, unnecessary motion, and defects. An eighth waste, unused employee creativity, was introduced recently (Liker, 2004). Table 4 explains each waste type. Lean thinking focuses on the reduction of waste; therefore, it affects the organization's finances positively. Lean thinking states that only the reduction of waste or cost will increase profits (Quesada et al., 2011).

Table 4. Types of wastes in Lean Thinking

Type of Lean Waste	Definition
Overproduction	More articles are produced than the established on the production order, causing an increase in inventory, and therefore costs increase.
Waiting	Idle equipment or workers.
Unnecessary transportation	Avoidable transportation of goods, parts, or information.
Over processing	Task performed the wrong way, producing wrong outputs, adding costs to the product or service.
Excess inventories	Excess raw material, work in process, and finished goods. This produces long waiting times, obsolescence, damaged products, unnecessary transportation, and holding and production costs.
Unnecessary motion	Any movement made by an operator that is unnecessary, such as searching for tools or parts.
Defects	Products that do not meet the customers' requirements.
Unused employee creativity	Not listening to employees, wasting their potential.

Source: Quesada et al., 2011

Lean thinking uses four main concepts that can only be applied with the commitment of an organization's leadership. The four concepts are explained in Figure 2.



Source: (Quesada et al., 2011)

Figure 2. Lean Thinking: Four Basic Concepts

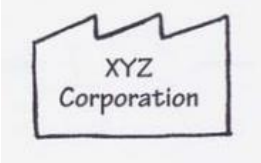


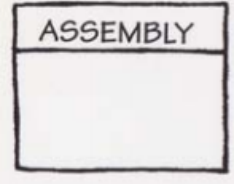

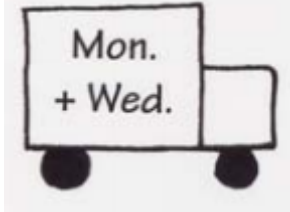
2.3.1 Value Stream Mapping (VSM)

Lean thinking focuses on the idea that only value-added activities should be executed. Value stream mapping is a Lean tool that helps to identify VA and NVA activities in a company's value chain (Quesada et al., 2011). In a manufacturing company, the value stream refers to the moment when raw material arrives until it is a finished product ready to be dispatched. Value stream mapping allows the observation of flow and communication within the process. Moreover, this tool permits all stakeholders of a company to picture and understand how the process works. Value stream maps are established in two states; current and future. Current refers to how the current process is taking place, and future represents how it is expected to work after improvements have been made (Nash and Poling, 2008).


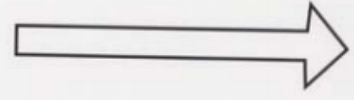

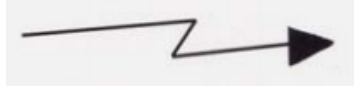
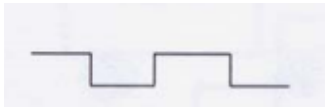

Value stream mapping not only reflects current process activities, but it also shows the flow of products and information, relationship with suppliers, and customer

needs. A VSM provides lead times, process availability, production scheduling methods, and the comparison of the total time of value-added activities against the overall lead time of the process (Quesada et al., 2011). The construction of a VSM requires a list of figures that are explained in Table 5.

Table 5. Important Considerations in Value Stream Mapping

Metric	Icon	Definition
Outside sources		Used to represent customers and suppliers.
Scheduling		Describes an information flow
"Go see" scheduling		Schedules based on checking inventory levels.
Process box		Indicates the type of process in which the material is flowing. The process box stops wherever the processes are disconnected, and the material flow stops.
Inventory		It indicates the inventory levels at each moment of the process.
Method and frequency of shipping		Indicates how the product is being shipped to the customer and at what frequency. It will also indicate how it is being received from the supplier and at what frequency.

Continuation of Table 5

Metric	Icon	Definition									
Push arrow		It indicates the movement of production by push.									
Finished goods to the customer		Shows the movement of the final product to the customer									
Manual information flow		Shows a manual flow of information									
Electronic information flow		Shows an electronic flow of information									
Databox	<table border="1" data-bbox="545 806 854 974"> <tbody> <tr> <td>Monthly demand</td> <td>10,080</td> <td>Unit</td> </tr> <tr> <td>Daily demand</td> <td>504</td> <td>Unit</td> </tr> <tr> <td>Takt time</td> <td>57.14</td> <td>Secs</td> </tr> </tbody> </table>	Monthly demand	10,080	Unit	Daily demand	504	Unit	Takt time	57.14	Secs	It indicates numeric values and units relevant to the process.
Monthly demand	10,080	Unit									
Daily demand	504	Unit									
Takt time	57.14	Secs									
Timeline		Compiles production lead time									
Operators		Specifies the number of operators necessary for a particular activity									

Sources: Rother et al., (1999); Quesada et al., (2011)

Apart from the figures, it is also necessary to use specific metrics that will help to obtain numeric values through the construction of the respective VSM; these metrics are explained in Table 6.

Table 6. VSM metrics

Metric	Description	Units
Order to Shipment/ Transit Time	The order to shipment is the period when an order is placed from the customer until it is ready for shipment. The Transit time is the time that the final product takes to be the shipment takes to be delivered from the supplier that provides raw material until the final customer gets his Thermally Modified (TM) wood.	Days
Lead Time/ Total Lead time	Lead time is the total time that takes a product to reach its final point (Order to shipment + Transit Time). For the case of the Total Lead Time, it is an average of inventory days and the lead time.	Days
Monthly and daily demand	Expresses how much product the customer requests	Units
Cycle time (CT)	How often a process completes a product. Also, the time it takes for a worker to go through all their work before elements before repeating them.	Seconds (s)
Setup Time (ST)	Time to switch from producing one product type to another	Hours (h)
Number of workers	Number of people needed to operate the process	
Available time	Working time minus any break	Seconds (s)
Takt time	It represents how much time it takes to produce a unit	Seconds (s)
Process Time	The process time is the amount of time that the mill needs to process wood into TM wood.	Days / Seconds
Inventory	In the value stream, inventory is: <ul style="list-style-type: none"> • Wood prepared to thermally-modify. • Wood being treated by the chamber. • TM wood ready. Inventory levels are calculated, dividing each inventory quantity by the daily customer requirements.	Days
Average days on Hand (ADOH)	Average days that wood stands at the mill waiting to be thermally modified.	Days' Supply
Minimum Order Quantity (MOQ)	The minimum amount of TM wood processed.	An Average Batch
Cost of Fulfillment	The cost involved in logistics activities: <ul style="list-style-type: none"> • Wood on Hold at Yard Cost • Thermal Modification Inventory Carrying Costs	Dollars (\$)
Carrying Cost	Holding Cost involved in storage TM wood.	Dollars (\$)

Sources: Rother et al., (1999); Quesada et al., (2011)

According to (Quesada et al., 2011), six main steps need to be followed for the construction of a VSM. The first step takes care of the identification of the customers and the suppliers, and uses them as control icons. It also calculates the daily production and shipping requirements based on the customers' needs see equation 1.

$$\text{Daily demand (unit/day)} = \frac{\text{monthly demand(unit/month)}}{\text{monthly work days(day/month)}}$$

Equation 1. Daily demand in units/day

Once the daily demand is calculated, it is necessary to obtain the value of how much time it takes to produce a unit, this is called the takt time, and it is obtained using equation 2.

$$\text{Takt time} = \frac{\text{Available time(sec/day)}}{\text{Daily demand(unit/day)}}$$

Equation 2. Takt time

Step number two indicates the method and frequency of shipping from the supplier. For the customer, this is shown through icons on the VSM. Step number three shows the addition of all the processes to the map. Every process figure includes the non-value-added and value-added timeline as mentioned in Table 3. Non-value-added is indicated as the peak of the line and VA as the valley of the line, using seconds as units. Step number four makes use of communication methods to indicate if the interaction with the customers and suppliers is via an electronic format or through a manual form. It also shows how internal communication is run. The fifth step indicates the inventory levels at each point of the process, and these levels are calculated using equation 3. In this step, it is necessary to note if the process is run by a push format (production schedule based on the forecast). As for the last step, it proceeds with the calculation of NVA using equation 4 and VA times through the sum of all process times used to create the product. It is essential to indicate shifts

per day, the available time, total lead time, process time, and present the NVA and VA times as a percentage of total lead time.

$$\text{Inventory level} = \frac{\text{Inventory quantity}}{\text{Daily demand}}$$

Equation 3. Inventory level

$$NVA = \text{Total lead time} - VA$$

Equation 4. Non-value added activities.

3 Goals and Objectives

Thermally modified wood producers need to determine the best marketing strategies to increase market share of this material, since the barriers and drivers of adoption of TMW would allow them to understand the potential of the market. Also, TMW producers are still looking for the most efficient practices to produce TMW, since every schedule used to modify wood provides a different mechanical performance.

The literature shows that when products have standards, the market is more likely to accept them. The lack of information regarding the properties of TMW produced by different companies is a problem for producers. Architects are currently the primary market driver of TMW use. Ensuring they know about TMW would increase the market share. The following objectives are proposed for this study.

The goal of this project is to:

Increase the market awareness of TMW produced from low-value hardwood species, by increasing the primary customer's knowledge and acceptance of the material, while increasing the efficiency of producers.

The specific objectives are:

1. Determine primary marketing barriers and drivers that are impacting the consumption of TMW based on perceptions from architects.
2. Evaluate the variability of mechanical properties for TMW using yellow poplar (*Liriodendron tulipera*), red maple (*Acer rubrum*) and white ash (*Fraxinus americana*) currently manufactured in North America.
3. Develop a Lean Process Strategy in the production of TMW to improve the process, reduce the cost, and reduce waste in TMW production.

4 Methodology

This research involved three different objectives; market perception, product performance and variability, and three cases studies on the current practices of producing TMW. This section provides information regarding the development of the project.

4.1 Objective 1:

Determine primary marketing barriers and drivers that are impacting the consumption of TMW based on perceptions from architects.

4.1.1 Methods

The first objective of this project consists of evaluating the perception of TMW among architects, since they are the main clients of producers and distributors (Wardell, 2015). Knowing architects' perceptions about TMW would help producers increase market share adoption by providing needed information to architects, as well as understanding the current lack of drivers for the adoption of TMW products.

A survey was developed to study the perceptions of TMW specifically for east coast companies. The focus was to study the market on the east coast of the United States due to the abundant amount of yellow poplar, red maple, and ash. This would benefit the Appalachian region and it was necessary to limit the study region due to cost limitations. The methods used for this project could be expanded to study other sectors of United States. The survey included questions related to the performance and characteristics of TMW, including an understanding of mechanical performance (bending, modulus of elasticity, and surface hardness), water relationships (moisture repelling and shrinkage), durability (decay resistance and maintenance aspects), and visual aspects (color). The selection of these factors was due to how affected they were by the modification process, as well as how they related to most of the applications in which TMW was commonly used.

Different types of questions were formulated to capture the perceptions of the participating architects, including open, closed, and Likert items (Bruner et al., 2017). The final questionnaire was submitted to the Institutional Review Board at Virginia Tech to ensure there were no negative impacts of the survey on respondents.

Once the survey closed, all returned questionnaires were revised for accuracy and content reliability. Univariate and multivariate techniques were used to analyze the data and extract the most significant drivers and barriers impacting the consumption of TMW on the surveyed sample.

To meet the objective, the following hypotheses on Table 7 were investigated:

Table 7. Hypothesis for objective 1.

H ₁	The architects' familiarity with the strength performance of TM wood is independent of whether they have worked with TM wood products
H ₂	The architects' familiarity with the dimensional stability of TM wood is independent of whether they have worked with TM wood products
H ₃	The architects' familiarity with the pricing of TM wood is independent of whether they have worked with TM wood products
H ₄	The architects' familiarity with the species availability of TM wood is independent of whether they have worked with TM wood products
H ₅	The architects' familiarity with the non-toxic material of TM wood is independent of whether they have worked with TM wood products.
H ₆	The architects' familiarity with the aspect of TM wood is independent of whether they have worked with TM wood products.
H ₇	There is not a statistically significant association between the architect's business category and the strength familiarity of TM wood.
H ₈	There is not a statistically significant association between the architect's business category and the dimensional stability familiarity of TM wood.
H ₉	There is not a statistically significant association between the architect's business category and the product pricing familiarity of TM wood.

Continuation of Table 7

H ₁₀	There is not a statistically significant association between the architect's business category and the species availability familiarity of TM wood.
H ₁₁	There is not a statistically significant association between the architect's business category and the non-toxic familiarity of TM wood.
H ₁₂	There is not a statistically significant association between the architect's business category and the aspect familiarity of TM wood.
H ₁₃	There is not a statistically significant association between the architect's target audience and the strength familiarity of TM wood.
H ₁₄	There is not a statistically significant association between the architect's target audience and the dimensional stability familiarity of TM wood.
H ₁₅	There is not a statistically significant association between the architect's target audience and the product pricing familiarity of TM wood.
H ₁₆	There is not a statistically significant association between the architect's target audience and the species availability familiarity of TM wood.
H ₁₇	There is not a statistically significant association between the architect's target audience and the non-toxic familiarity of TM wood.
H ₁₈	There is not a statistically significant association between the architect's target audience and the aspect familiarity of TM wood.

The hypotheses were established based on a review of relevant literature, provided in section 2.2. Once the results were obtained, a descriptive analysis was conducted to analyze the responses in regard to both market barriers and drivers. The barriers were all those factors that make consumers not use the product or did not allow them to use it, such as cost or lack of familiarity with the product. The drivers were all those forces that made users want to use a product, such as durability and dimensional performance, as well as lack of toxic substances. With the perception of architects regarding TMW products, it would be useful to develop strategies and recommendations for the expansion of TMW markets.

The hypotheses were analyzed using ordinal logistic regression to assess the relationships listed in Table 7. An ordinal logistic regression evaluates if every coefficient for a determined categorical predictor shares a relationship (Minitab, 2019). The ordinal logistic regression calculates a coefficient for every term in the model. Values such as the coefficient (coef) and the standard error coefficient (SE coef), evaluate the probability of one of the outcome changes relative to another outcome, in this case, the different target audiences and business categories. The standard error measures the precision of the estimated selected coefficient (Minitab, 2019). The log-likelihood that Minitab computes is a maximized function that finds optimal values to estimate each one of the coefficients. The lower the value, the better, but in this case, since there were four terms in the model with different sample sizes, it was normal to see a higher log-likelihood value.

4.1.1.1 Questionnaire development

The questionnaire was structured in two sections; one section regarding the perception of TMW products among architects, from a technical and market perspective, and the other section was a set of demographic questions and general aspects of the company.

Initially, the questionnaire included an introductory section to the study, with the desired objective, alongside the researcher's contact details to support the cover letter mailed.

The questionnaire consisted of 20 questions grouped into two different sections. The first section included seven demographic questions about the size of the businesses surveyed in terms of gross sales, years of operation, and average distance to provide services. The gross sales values used to classify the company were determined under NAICS 541310 and 541320. These classifications under NAICS cover Architectural Services and Landscape Architectural Services, respectively. The second section of the questionnaire consisted of 13 marketing and technical questions about the perception of customers and architectures regarding TMW

products. Every respondent was required to answer the first seven questions, since the first section of the questionnaire asked the demographics questions and included one perception question regarding the marketing and technical aspects of TMW. Following the eighth question, only the respondents that distributed, manufactured, or used TMW in their business were asked to continue with the rest of the survey. At the end of the survey, the respondents were asked to provide any additional information or comments that could contribute to the research. Table 8 shows the bibliographical references used to build the questionnaire.

Table 8. Bibliography Used for Questions

Question	Bibliography
1 – 6.	Dillman et al., (2014); Rossi et al., (2013); Weisberg et al., (1996)
7	Esteves et al., (2009); Larsson-Brelid (2013); Espinoza et al., (2015)
8	Ray et al., (2005); Espinoza et al., (2015); Larsson-Brelid (2013)
9	Espinoza et al., (2015); Dillman et al., (2014);
10	Larsson-Brelid (2013); Espinoza et al., (2015)
11	Sandberg et al., (2015); Espinoza et al., (2015)
12	Sandberg et al., (2015); Espinoza et al., (2015)
13	Lynn, (2017) Espinoza et al., (2015)
14	Dillman et al., (2014); Espinoza et al., (2015)
15	Rossi et al., (2013); Dillman et al., (2014); Esteves et al., (2009); Espinoza et al., (2015)
16	Rossi et al., (2013); Dillman et al., (2014); Esteves et al., (2009); Espinoza et al., (2015)

Before the questionnaire was sent out, it was essential to conduct a pretest to help identify question variations, respondents' interest, attention, and understanding to increase the response rate (Hunt et al.,1982). According to UNESCAP (2004), pretesting should improve the quality of the data collected, reducing the survey cost and the development time.

The technique used to conduct the pretest was developed by Presser (1994), and Rothgeb (2007) called Expert Review. This technique consists of an individually based reviewer specializing in the field under study, who is capable of identifying difficulties in the questionnaire. The reasons this technique was selected were

based on time, expertise in the field, and also prior use by several authors (Madrigal, (2012); Li, (2002); Sanchez, (2011)).

The pretest was conducted using three experts (architects), and once they completed the questionnaire, no further recommendations were provided. After the pretest was concluded, the questionnaire was submitted to the Institutional Review Board (IRB) for Research Involving Human Subjects to ensure ethical guidelines were followed. The approval is in Appendix B.

This study consisted of two implementation modes to increase the response rate and to cover a larger population and reduce coverage error (Das et al., 2018; De Leeuw et al., 2011). The information collected from Chambers of Commerce only contained physical addresses, making these firms harder to contact through email. The contact information bought from the NAICS Association contained email addresses and these were selected for on-line contact. Also, all the firms included in the NAICS database and were duplicated in the Chamber of Commerce list, were removed from the mailing list to reduce mailing cost. Mail was only sent to those companies whose data was not obtained from the NAICS database.

4.1.1.2 Sample Frame using mail.

The questionnaire focused on the perception of architects regarding the use of TMW. The sample frame was identified from the current 'Architects' category that was listed in the Chamber of Commerce in the most populated counties from each state on the east coast of the U.S. The reason for working with the most populated counties from each state was due to factors such as timelines, cost, and availability of the information, since not every business was registered with the Chamber of Commerce and the most populated counties had higher numbers of firms. The selected counties are displayed in Appendix A.

4.1.1.2.1 Survey Implementation using mail survey mode

The implementation of a survey involves a combination of how attractive the survey is to the respondent and the strategy for getting the most replies from the population.

Since the survey mode for one portion of the population was via mail, to achieve a successful outcome, the questionnaire had to have an attractive visual design, proper communication with the survey recipients, and comprehensible questions (Dillman et al. 2014).

To obtain a higher response rate for a mailed survey, Dillman et al. (2014) recommended five necessary steps:

1. Pre-notice letter
2. Questionnaire
3. Reminder/Thank You postcard
4. Questionnaire replacement
5. Final reminder letter

In the first mailing, each recipient received an introductory cover letter explaining the purpose of the survey, along with the questionnaire with a tracking number for each recipient and a return envelope for mail.

Biemer et al., 2003 and Rea et al., 2005 recommended the use of a tracking number to identify the recipient's participation in the questionnaire and to take follow-up actions for non-respondents.

Dillman (2009) proposed a guideline to determine a structured timeline to develop a survey using mail as a communication channel. The time frame was two weeks, and used three communication forms, beginning with the cover letter, the questionnaire, and the return envelope. Two weeks after the primary communication forms, a reminder/thank you letter was sent, to encourage the non-respondents to participate. Two weeks following the reminder letter, the questionnaire with a modified cover letter was sent to non-respondents to express how vital their response was to this research, along with a return envelope. The dates for the survey implementation are summarized in Table 9.

Table 9. Survey Implementation Dates for Mail Survey Mode.

Correspondence	Date	Time Mark
Cover Letter and Questionnaire	July 17 th , 2019	Day 0
Reminder/Thanking Postcard	July 24 th , 2019	2 Week
Send Cover Letter 2 and Questionnaire.	July 31 st , 2019	4 Weeks

4.1.1.3 Sample Frame using the web mode.

For the sample frame that was surveyed via a website, the firms were qualified under NAICS 541310 and 541320. The contact list was purchased from the correspondent industry directory (SICCODE.com, 2019). The classification 5413 under NAICS covers architectural services and landscape architectural services.

4.1.1.3.1 Web Mode Survey Implementation.

The flexibility of a web questionnaire can be seen from two perspectives, surveyor and respondents. From a surveyor perspective, sending the questionnaire by email with the URL to access the web survey was easier than setting up an interview, meeting online, or mail surveys. Analyzing the results was also easier, since there is software to build a questionnaire and to help analyze the results, making it faster. From a respondent's perspective opening a URL or QR code can be either harder or easier. Harder if the respondent is not familiar with email and does not know how to open the URL on a browser to access the questionnaire, and/or does not understand how to fill out and answer all the items in the questionnaire. It is easier for the population with higher education and that understands how to use the Internet to complete the survey (Dillman, 2014).

Qualtrics is a company that provides a variety of tools, screen resolution options, and browser flexibility, making the development of a survey easier. Since Virginia Tech has a partnership with Qualtrics, the development of the survey as well as distribution, used Qualtrics. Table 10 shows the timeline for the implementation of the web survey used in this study.

Table 10. Correspondence Timeline for the Implementation of Web Survey.

Correspondence	Date	Time Mark
Cover Letter and Questionnaire	July 29 th , 2019	Day 0
First Email Reminder	August 5 th , 2019	1 Week
Second Email Reminder	August 12 th , 2019	2 Weeks
Third Email Reminder	August 19 th , 2019	3 Weeks

Once the responses were obtained, the first step was to assess the non-response bias, which was determined by the business category, target audience, and business size. If the pattern between the waves of responses were not different, it was safe to assume the respondents had shared characteristics, since they came from the same population and were representative.

4.2 Objective 2:

Evaluate the variability of mechanical properties for TMW using yellow poplar (*Liriodendron tulipera*), red maple (*Acer rubrum*), and white ash (*Fraxinus americana*) currently manufactured in North America.

The purpose of this evaluation was to determine the mechanical performance variability across the three companies involved in the project. Three different TMW species were provided from the three companies to measure their mechanical performance.

The evaluation provided information regarding the variability of commercially available TMW performance, which, if low, could be used to educate customers of the advantages and disadvantages compared to similar wood products and thus potentially increase the market share of TMW.

To conduct each mechanical test adequately, ASTM and AWPA procedures were followed. The hypotheses proposed in Table 11 were designed to evaluate variability between companies across the three species selected regarding their mechanical performance.

Table 11. Hypothesis for Objective 2.

Test	Null Hypothesis	Variable
Yellow Poplar- MOR	H ₁ : The MOR mean values of yellow poplar are the same between companies	Modulus of Rupture
Yellow Poplar- MOE	H ₂ : The MOE mean values of yellow poplar are the same between companies	Modulus of Elasticity
Yellow Poplar- Radial S	H ₃ : The radial shrinkage mean values of yellow poplar are the same between companies	Radial Shrinkage
Yellow Poplar- Tangential S	H ₄ : The tangential shrinkage mean values of yellow poplar are the same between companies	Tangential Shrinkage
Yellow Poplar- Hardness	H ₅ : The hardness mean values of yellow poplar are the same between companies	Hardness
Yellow Poplar- EMC	H ₆ : The EMC mean values of yellow poplar are the same between companies	EMC
Yellow Poplar – Durability: <i>Gloeophyllum trabeum</i>	H ₇ : The percentage of weight loss with <i>Gloeophyllum trabeum</i> mean values of yellow poplar are the same between company B and C	<i>Gloeophyllum trabeum</i>
Yellow Poplar – Durability: <i>Trametes Versicolor</i>	H ₈ : The percentage of weight loss with <i>Trametes versicolor</i> mean values of yellow poplar are the same between company B and C	<i>Trametes Versicolor</i>
Red Maple – MOR	H ₉ : The MOR mean values of red maple are the same between companies	Modulus of Rupture
Red Maple - MOE	H ₁₀ : The MOE mean values of red maple are the same between companies	Modulus of Elasticity
Red Maple - Radial S	H ₁₁ : The radial shrinkage mean values of red maple are the same between companies	Radial Shrinkage
Red Maple - Tangential S	H ₁₂ : The tangential shrinkage mean values of red maple are the same between companies	Tangential Shrinkage
Red Maple - Hardness	H ₁₃ : The hardness mean values of red maple are the same between companies	Hardness

Continuation of Table 11.

Test	Null Hypothesis	Variable
Red Maple - EMC	H ₁₄ : The EMC mean values of red maple are the same between companies	EMC
Red Maple – Durability: <i>Gloeophyllum trabeum</i>	H ₁₅ : The percentage of weight loss with <i>Gloeophyllum trabeum</i> mean values of red maple are the same between company B and C	<i>Gloeophyllum trabeum</i>
Red Maple – Durability: <i>Trametes versicolor</i>	H ₁₆ : The percentage of weight loss with <i>Trametes versicolor</i> mean values of red maple are the same between company B and C	<i>Trametes Versicolor</i>
Ash – MOR	H ₁₇ : The MOR mean values of ash are the same between companies	Modulus of Rupture
Ash - MOE	H ₁₈ : The MOE mean values of ash are the same between companies	Modulus of Elasticity
Ash - Radial S	H ₁₉ : The radial shrinkage mean values of ash are the same between companies	Radial Shrinkage
Ash - Tangential S	H ₂₀ : The tangential shrinkage mean values of ash are the same between companies	Tangential Shrinkage
Ash - Hardness	H ₂₁ : The hardness mean values of ash are the same between companies	Hardness
Ash - EMC	H ₂₂ : The EMC mean values of ash are the same between companies	EMC
Ash – Durability: <i>Gloeophyllum trabeum</i>	H ₂₃ : The percentage of weight loss with <i>Gloeophyllum trabeum</i> mean values of ash are the same between company B and C	<i>Gloeophyllum trabeum</i>
Ash – Durability: <i>Trametes Versicolor</i>	H ₂₄ : The percentage of weight loss with <i>Trametes versicolor</i> mean values of ash are the same between company B and C	<i>Trametes Versicolor</i>

4.2.1 Methods

4.2.1.1 Task 1.

The first stage consisted of the identification of the ASTM and AWWA standards for each performance metric selected for the project. The selected performance metrics included surface hardness, dimensional stability, static bending, the equilibrium of moisture content, and durability against fungi. It was necessary to understand each one of the procedures and properly manage each apparatus to get accurate results. The sample size was limited to 14 samples per specie by each company. Sample size was limited, since material for each specie was donated. Each company donated a total of 42 samples for a total of 126 samples tested.

Specimens for each specific test were prepared from different individual boards to increase reliability. Tagging each board was fundamental to avoid sampling errors from specimens coming from the same board, which could lead to inaccurate results. Each board sample was tagged alphanumerically with the initials of the specie and a two digit number.

Once the specimens were cut to the dimensions provided by each standard, the samples were stored in a temperature and humidity-controlled room with conditions set to $23\pm 2^{\circ}\text{C}$ and $67\pm 1\%$ RH. Each specimen was weighed every week and once the weight of each specimen was constant over time, the sample was determined to have reached the equilibrium of moisture content and was ready to be tested. Several authors have reported that TMW decreases the amount of water that can be held, due to the decrease of hydroxyl groups, causing the EMC to be lower compared to untreated wood. (Jämsä et al., 2001).

The results from the test were stored on a generic spreadsheet with the information from the company that provided the board, the species used, the performance metric evaluated, temperature and humidity, and the test results. Each of these metrics were evaluated with the corresponding procedure, as shown in 4.2.1.1

4.2.1.1.1 Hardness ASTM D143 (modified)

Hardness is defined as the resistance of wood to indentation using a 25.4 mm ball also known as the Janka hardness test and is measured using the ASTM D143 standard. The focus of this standard is to test the properties of wood by evaluating small clear specimens and examine the procedures for different mechanical and physical properties, specimen size, moisture content, temperature, and rate of loading. All specimens were weighed before and after testing. To determine the performance of the thermal modification on the performance of the surface hardness by the ASTM D143 (2014), the specimens were cut to the dimensions of 1 by 2 by 6 inches (50.8 by 50.8 by 152.4 mm).

The hardness test was conducted on an MTS Test Machine using a 1360.80 kg load cell operating at a speed of 0.25 in. (6 mm)/min. The test used a ball of 0.444 inches in diameter, with a projected area of the ball on the test specimen of 1 cm², with two penetrations on the tangential surface.

4.2.1.1.2 Static Bending (MOE, MOR) ASTM D143

The next mechanical test determined the performance of static bending by the ASTM D143 (2014), the size of specimens were 1 by 1 by 16 inches (25 by 25 by 410 mm). The span length used was 14 inches to maintain a minimum span-to-depth ratio of 14. The bearing block's radius used was 1 ½ and the load applied to the specimen was on the tangential surface at a rate of 0.05 in/min (1.3 mm/min). The load-deflection curves were recorded, and the test finished until the maximum load was reached for all static bending tests.

4.2.1.1.3 Radial and Tangential Shrinkage – ASTM D143 (modified)

The next physical test determined the dimensional stability performance by estimating the radial and tangential shrinkage by ASTM D143 (2014). The size of specimens was modified with values of 0.75 by 0.75 by 1 inch (19 by 19 by 25 mm), due to dimension limitations of the lumber provided. Instruments such as a micrometer were suitable for accuracy. Several authors have conducted the test

using the size of specimens with similar dimensions that were used in this study, as modified from the standard (Zanuncio et al., 2018; Brito et al., 2018).

The specimens were weighed, and their length was measured before oven drying. The oven was set at conditions of $103 \pm 2^\circ\text{C}$ until a constant mass was reached. Once the specimens reached constant mass, their weight and length were measured again.

4.2.1.1.4 Durability AWP A E10

The next test determined the durability performance of wood against fungi following the standard AWP A E10 (2016). This method evaluates the resistance of wood-based material to decay under controlled laboratory conditions. The standard suggests a variety of fungi that could be used and provides the recommended procedures and equipment to conduct the test. To assure that the proper procedures were followed, the author contacted an expert (Dr. Adam Taylor) who used these procedures regularly. The author visited the Tennessee Forest Products Center at the University of Tennessee and was taught the procedures in the laboratory. For these tests, the specimens were cut into cubes of 19 mm (0.75 in.) and exposed to *Gloeophyllum trabeum* (brown-rot) and *Trametes versicolor* (white-rot) fungi, which are recommended by the standard, and the Forest Products Lab. Specimens were free from knots and abnormal amounts of resin or gums and without visible evidence of fungus infection. The samples were exposed to environmental conditions of 21°C and 65% relative humidity until they reached an equilibrium. The bottles, feeder strips, samples, and materials were sterilized with an autoclave at 121°C for 30 minutes. The bottles were then inoculated with soil, a feeder strip, and the fungus inoculum at 26.7°C and 70% relative humidity until feeders were covered by mycelium (three weeks). When the mycelium covered the feeder strip, the wood block sample was added and stored in a dark incubation room. After 12 weeks of incubation the mycelium was removed and brushed, then the blocks were oven-dried and placed in a conditioning chamber at 21°C and 65% RH to reach EMC to then compute the weight loss percentage using Equation 5.

$$\text{Weight loss Percentage} = \frac{100 (W_1 - W_2)}{W_1}$$

Equation 5. Weight loss Percentage

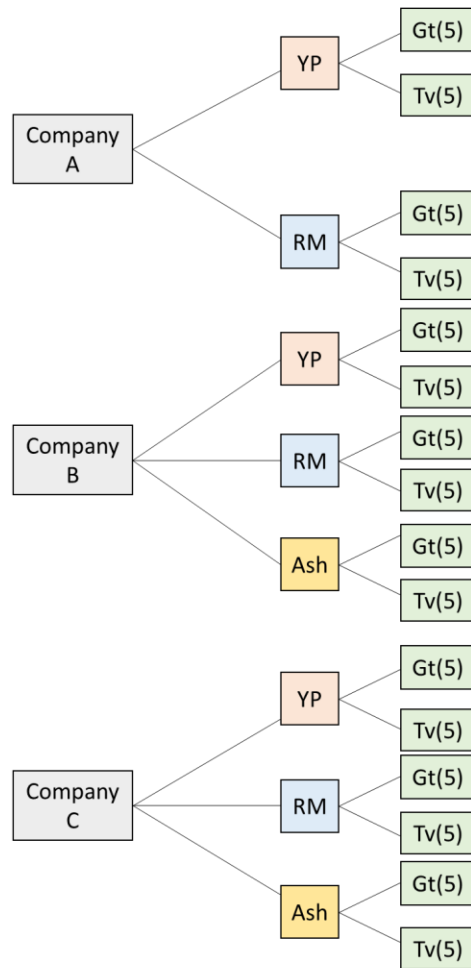
Where,

W_1 : Weight after sample reaches equilibrium of moisture content before test.

W_2 : Weight after sample reaches equilibrium of moisture content after test.

Testing Design:

The testing design proposed for the durability test is shown in Figure 3. There were three companies providing samples from three different species for the project. Five samples from each species provided by each company were tested with two different fungi: *Gloeophyllum trabeum* and *Trametes versicolor*. The selected fungi were recommended by the AWWA E10 (2017) standard in section 6.1.



Gt (5): Five samples with *Gloeophyllum trabeum*
 Tv (5): Five samples with *Trametes versicolor*

Figure 3. Testing design

Since this testing involved two different fungi and required over 16 weeks to be conducted, which was longer than the other mechanical testing, only two replicates per fungus were used. Also, having more than two replicates from each company would have made the sample size complicated to handle, due to the capacity limitations for storing the samples for conditioning. The sample size used by several authors was between six and nine samples per specie with no replicates specified (Unsal et al., 2009; Shi et al., 2007) Samples from company 2 were not provided before the testing began.

4.2.1.1.5 Equilibrium of Moisture Content (EMC) ASTM D4933

ASTM D4933-16 (2016) was used to precisely estimate the equilibrium of moisture content (EMC) of each treatment, company, and species. Each specimen's size was 19 by 25 by 19 mm. The first step was to condition the samples until they reached constant mass at conditions of 21°C and 65 RH%. Periodic weighing was done to record the mass changes and make sure the mass was constant over the time. Then the samples were oven-dried at 103°C for at least two days, until constant mass was reached, and the mass was recorded to estimate the EMC percentage of each sample.

4.2.1.2 Task 2

Once the results of the test were obtained, an analysis of variance (ANOVA) was conducted to understand the variability between companies and to answer each hypothesis established in Table 7 of this objective.

To conduct the ANOVA, all the assumptions were met with an $\alpha = 0.05$. The error was recommended by Lindenmayer (2005). The significance level is the weight expressed as the p-value. "*The probability of obtaining a value of the test statistic that is as likely or more likely to reject H_0 as the actual observed value of the test statistic*" (Ott, 2015). If the significance value was small, the sample would fail to support the null hypothesis. To support the ANOVA, a multiple comparison procedure was conducted using the Tukey procedure. This test was used to measure the significance between different means (Tukey, 1949).

4.3 Objective 3:

Develop a Lean Process Strategy in the production of TMW to improve the process, reduce the cost, and reduce waste, in TMW production.

4.3.1 Methods

4.3.1.1 Task 1.

The case study approach was used to develop a Lean process strategy that had an approach closer to the current practices of TMW producers. The author partnered with three companies in the United States that agreed to provide samples for testing and information regarding their current practices to produce TMW products. An overall description of the companies is displayed in the results section 5.3.1 for this objective. This study focused on the manufacturing process of TMW, and this means that it did not include a study of the entire supply chain management. A case study approach was used since, according to Yin (2009), a case study investigates a real-life phenomenon in depth and within its real-life context, especially when the boundaries of the phenomenon and contextual conditions are not evident between them. Yin (2009) referred to the unit of analysis as the “case is.” The case study of this research studied the production process of TMW across three companies. Yin (2009) further stated that the case study’s unique strength is its ability to deal with a full variety of evidence such as documents, artifacts, interviews, and observations.

The companies involved in this study provided the necessary information for the fulfilment of this objective. Yin (2009) recommended three tests in the interest of assuring high-quality research. The three tests are shown in Table 12.

Table 12 Quality Research Design

Test	Case Study Tactic
Construct Validity	Multiple sources of evidence to conduct to conclusions
External Validity	Analytical generalization of concepts and model development
Reliability	Case study protocol and establishment of documentation procedures

Source: Yin, 2009

The next section explains each specific objective, including the activities that were conducted, the tools necessary, and finally, the expected outputs for each step.

4.3.1.1.1 Activities Conducted

To understand the current manufacturing process and the different activities involved the author coordinated with three different wood companies on the east coast of the United States. Each company was referred to as company 1, 2, or 3. Meetings, interviews, and tours throughout the facilities were conducted to collect data that helped map out activities involved in TMW production.

4.3.1.1.2 Tools and Methods

Value stream mapping (VSM) was the Lean tool selected for mapping the current manufacturing process of TMW for each company visited; this means that three initial VSM were developed. The Lean logistic metrics that were considered in the framework came from literature and are reviewed in section 2.3.1. Existing parameters extracted from the VSM technique and new metrics were used for elaboration of the VSM. The Lean metrics selected allowed for an adequate measurement of the operations and processes, representing the state of the system. Table 5 in the literature review shows the metrics used, their descriptions and units.

4.3.1.1.3 Expected Outputs

A detailed description of the TMW process at each company was obtained. The selected metrics allowed identifying each subprocess involved, takt time, machinery, labor, and inventory levels, which were then represented in a value stream map to provide an overview of the situation of each manufacturing process.

4.3.1.2 Task 2

This task focused on measuring the productivity, efficiency, inventory levels, production costs, and lead times metrics that helped evaluate the activities that were part of the manufacturing process of TMW.

4.3.1.2.1 Activities Conducted

For the second task, calculations were conducted to obtain numeric values for productivity, efficiency, inventory, production costs, and lead times.

4.3.1.2.2 Tools and Methods

The metrics needed to develop the VSM were calculated using Excel. Once the data was in the program, the formulas mentioned in the literature review were used to obtain the results.

4.3.1.2.3 Expected Outputs

The second task focused on achieving numeric values for inventory levels, production costs, and lead times. These results included percentages for productivity and efficiency, facilitating the comparison of the three companies.

4.3.1.3 Task 3

This task focused on identifying the improvement opportunities and non-value activities in the manufacturing process of TMW.

4.3.1.3.1 Activities Conducted

Once the three value stream maps and all the numeric values were calculated, the next activity was identifying improvement opportunities in the manufacturing process. The values obtained from each company were compared to validate the findings. Even though numeric values were used, it was also necessary to point out the process problems and possible improvements.

4.3.1.3.2 Tools and Methods

Brainstorming with a multi vote tool was conducted with Dr. Quesada, Dr. Bond, a hired intern and the author to prioritize problems and Ishikawa diagrams were created for each of the three processes observed to find improvement opportunities.

4.3.1.3.3 Expected Outputs

The expected output of the task was to identify improvement opportunities in the manufacturing process of the three selected companies.

4.3.1.4 Task 4

The last task in this objective was to suggest an improved manufacturing process for TMW, solving the current issues, and setting up a standardized production process with respective cost models.

4.3.1.4.1 Activities Conducted

This task was dedicated to designing an improved process for TMW production, including a cost model.

4.3.1.4.2 Methods and Tools

Value stream mapping and flowcharts were the selected engineering tools for representing the improved manufacturing process.

4.3.1.4.3 Expected Outputs

This task created a future VSM and a flowchart of the process. This proposal included data related to inventory costs which considered the inventory at each phase of the VSM, the required demand, raw material ordering, and workforce.

5 Results and Discussion

In this chapter the results obtained to answer each objective are presented and discussed. The development of each objective, limitations, and results are detailed. The results and discussion are presented according to the order of each objective.

5.1 Objective 1: Market Perception

Thermally modified wood has been present in the U.S market since Westcorp introduced the product in 2004 at the International Woodworking Fair in Atlanta. Since then, manufacturers have been involved in the production of TMW products. The product itself has been around since the 1990s when the European market started showing interest in non-toxic wood products.

This section summarizes the findings related to answering the first objective regarding the market analysis conducted in the eastern United States. The focus of this objective was to develop information regarding the perception of architects regarding TMW, with the goal of assisting manufacturers with information on how they could increase their market share of this material. Espinoza (2015) conducted a study from the producer's perspective to determine marketing strategies but did not address the perspective of consumers to understand the barriers and drivers of TMW use.

A total of 146 responses were obtained from web and mail surveys. Forty-seven surveys came from the mail mode and 99 from the web mode. These 146 responses correspond to 2% of the total population of 8000 firms, where 5950 were from the NAICS database and 2050 were from Chamber of Commerce databases. The response rate from the mail mode was 2% and the web mode was 2%. Out of the total number of responses obtained, only 22 of the respondents answered question 8, meaning that they worked with TMW products and continued the survey. The rest of the respondents answered the first seven questions regarding the demographics of their respective businesses and returned the questionnaire. With only 22

respondents indicating they had worked with TMW; the results limited the extrapolation of these results from the sample towards the entire population. However, knowing that 85% of respondents had not worked with TMW, was a strong indication that there was little awareness of TMW in the architectural community on the east coast of the United States.

The limitation of not enough responses would not provide an accurate representation, so the results were tested with a non-response bias test to determine if the respondents were from the same population. To assess the non-response bias, an analysis of the waves of responses from the online mode was conducted based on the respondent's business category (question 6) and product recommendation (question 17). One wave of response is the amount of responses that are obtain after sending the respondents the survey or a remainder to complete the questionnaire. Since the first wave had the most responses, the other three waves were grouped to conduct a two-sample T-test.

The test hypothesis is:

- Null hypothesis = 1st wave mean – 2nd wave mean = 0
- Alternative hypothesis = 1st wave mean – 2nd wave mean \neq 0

Figure 4 shows the Minitab output form the two-sample T-tests conducted, Figure 4 A shows the results obtained from the T-test for the business category question and Figure 4 B, the results obtained from the production recommendation.

Figure 4 A

Descriptive Statistics

Sample	N	Mean	StDev	SE Mean
1st Wave	55	2.273	0.732	0.099
2nd Wave	44	2.386	0.841	0.13

Estimation for Difference

Difference	95% CI for Difference
-0.114	(-0.433, 0.206)

Test

Null hypothesis	$H_0: \mu_1 - \mu_2 = 0$	
Alternative hypothesis	$H_1: \mu_1 - \mu_2 \neq 0$	
T-Value	DF	P-Value
-0.71	85	0.481

Figure 4 B

Descriptive Statistics

Sample	N	Mean	StDev	SE Mean
Wave 1	8	1.500	0.535	0.19
Wave 2	14	1.214	0.426	0.11

Estimation for Difference

Difference	Pooled StDev	95% CI for Difference
0.286	0.467	(-0.146, 0.717)

Test

Null hypothesis	$H_0: \mu_1 - \mu_2 = 0$	
Alternative hypothesis	$H_1: \mu_1 - \mu_2 \neq 0$	
T-Value	DF	P-Value
1.38	20	0.182

Figure 4. Two-sample T-test for Non-response Bias

The results from the test showed that both samples were not statistically different, which meant that the respondents were a good sample representation coming from the same population. This approach was also conducted by Johnson et al., (2017), to determine the heartrate difference between respondents and non-respondents.

5.1.1 Demographic Questions

The demographic responses were divided into two groups based on the answer obtained from question 8, “Does your company distribute, manufacture, or work with TMW in your business?”. If the respondents answered this question with “No,” they were required to return the survey; if not, they proceeded by answering the market and technical questions regarding TMW.

Question 1a on the survey was, “What were your gross sales or revenues for your most recent fiscal year (2018)?”. It was a single choice entry question, with eight different options. The majority of respondents reported their gross sales were

between 0 - \$2.5M, 56% for those that worked with TMW products and 77% of those that did not.

Question 1b was about average growth of sales, where 68% and 83% of the companies worked and did not work with TMW products respectively, responded that they had an average growth in sales of 1-10%.

The responses for Question 1c are displayed in Figure 5. The question was about the architects' target audience, where residential (37%) and commercial (29%) were the most common responses from the respondents that worked with TMW. Also, the most common response for those that did not work with TMW products was commercial and residential, with 36% and 28%, respectively.

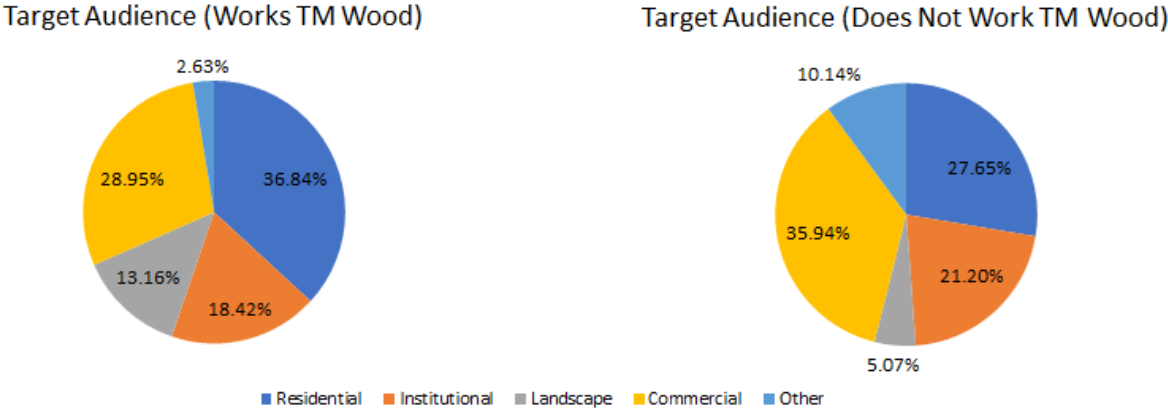


Figure 5. Target Audience Responses.

Question 1d in the demographics section was related to the average distance that they provide service, and 50% of the respondents provided services from 0-50 miles and 27% from 100-150 miles for the respondents that worked with TMW . Also, the most common average distance for those respondents that did not work with TMW had 39% of responses between 0-50 miles.

Question 1e displayed the amount of years in business. Most of the respondents that worked with TMW products had more than 20 years in service (59%), and 32% had

been in business for 11-20 years. For the respondents that did not work with TMW products, most of the respondents (71%) had been in business for more than 20 years. The second question was regarding the business category that they belonged to. Nine percent were in the construction business, 50% belonged to an architectural service, 5 % belonged to contractor services, and 36% selected Other. The response option that was considered as “Other,” corresponded to Architectural and Interior Design and Landscape Architecture. Of the respondents who did not work, 70% selected “Architectural/Civil Engineer Services.”

Table 13 summarizes the responses obtained from the demographic questions, based on the most selected item from each question, respectively, for both groups studied. By comparing the two groups studied in Table 13, the results did not highlight any important findings.

Table 13. Summary of Demographic Responses

Question	Works TM wood	Does not work TM wood
1) Gross Sales between 0-\$2.5M	56%	77%
2) Average growth sales between 1-10%	64%	64%
3) Target Audience (Commercial and Residential)	29% and 37%	36% and 28%
4) Average Distance between 0–50 miles.	50%	39%
5) More than 20 years in business	59%	71%
6) Architectural/Civil Engineer Service	50%	70%

5.1.2 Technical and Market Questions

The next set of questions measured the respondent’s perceptions of the market for the technical aspects of TMW. The third question asked about the familiarity of the mechanical and physical performance of TMW using the Likert scale. Table 14 displays the results regarding how familiar the respondents were to different characteristics of TMW based on the respondent's perception.

Table 14. Answers for Question Three from all the respondents.

Question	Not at all familiar		Not so familiar		Somewhat familiar		Very familiar		Extremely familiar		Total
	%	Count	%	Count	%	Count	%	Count	%	Count	
Strength	44%	64	12%	17	36%	53	7%	10	1%	2	146
Dimensional stability	44%	64	11%	16	32%	47	12%	17	1%	2	146
Product pricing	53%	78	24%	35	17%	25	5%	7	1%	1	146
Species availability	52%	76	27%	39	16%	23	5%	7	1%	1	146
Non-toxic material	47%	69	21%	31	22%	32	8%	12	1%	2	146
Aspect	48%	70	18%	26	25%	37	7%	10	2%	3	146

The Likert scale used has five responses that measure the familiarity levels of the respondents. “Not at all familiar” was the response level for respondents that had no knowledge of the factor measured. The “Not so familiar” response was for respondents that had heard of an effect the factor had on TMW. The “Somewhat familiar” was a response for respondents who had a better understanding of the factor measured but still were not completely familiar with TMW. The “Very familiar” factor was for respondents who had knowledge of TMW factors. Finally, the “Extremely familiar” response was for respondents who understood the property and knew about the effect of this factor on TMW.

The first two metrics studied were strength and dimensional stability, where most of the respondents were “Not at all familiar” with the product performance regarding the two-mechanical metrics, with 44% for strength and 44% for dimensional stability. There were respondents that selected “Not so familiar” with strength (12%) and dimensional stability (11%). Also, a considerable percentage of respondents were “Somewhat familiar” with both metrics (36% and 32%), strength, and dimensional

stability, respectively. Around 7% and 12% of the respondents selected “Very familiar” with the strength and dimensional stability respectively, and only 1% of the respondents selected “Extremely familiar.” Regarding product pricing, most of the respondents (53%) were “Not at all familiar.” A similar response was seen with the availability of the species, where most of the respondents (52%) considered themselves “Not at all familiar” with the species that were available for TMW products. The response regarding the non-toxic material metric, most of the respondents (47%), were “Not at all familiar” with TMW being considered a chemical-free product. For the metric that covered the color and the smell of TMW products, 48% of the respondents were “Not at all familiar,” and 25% of the respondents considered they were “Somewhat familiar” with the metric. Overall, most of the respondents were “Not at all familiar” with TMW factors, but there was also a high percentage of respondents who knew something or had an idea of TMW factors.

The TMW factor that most of the respondents were familiar with (Very familiar and Extremely familiar) was dimensional stability. which is one of the most improved physical properties of the TMW process. The TMW factors that had the least familiarity among the respondents were species availability and product pricing. For producers, product pricing might be one of the most important aspects because one of the main purposes of the TMW process is to increase the value of low-value species such as yellow poplar, red maple, and ash. The conclusions in Espinoza’s study (2015) showed that producers’ customers were not sensitive to prices when these were compared to mainstream markets, meaning that customers usually cared about the price of wood products, which was contradicted in the results where respondents were not familiar with the prices for TMW.

Evaluating differences in perceptions about TMW between those who have used the material and those who have not, could potentially identify different marketing strategies for the two groups. To evaluate if there was a statistical difference between the perception of the architects who had worked with TMW products and those who had not, a hypothesis was established in section 4.1.1. Since the data obtained was

ordinal, the data were summarized in contingency tables, and Chi-Square tests were conducted. The results are displayed in Table 15.

Table 15. Hypothesis Testing Summary with Chi-Square (P-Value).

Hypothesis	Variable	Test Statistic		Hypothesis Accepted
		Questions	P-Value	
H ₁	Strength	Question 7 Vs Question 8	0.000	H1: There is a significant statistical difference between the variables.
H ₂	Dimensional Stability	Question 7 Vs Question 8	0.000	H2: There is a significant statistical difference between the variables.
H ₃	Product Pricing	Question 7 Vs Question 8	0.000	H3: There is a significant statistical difference between the variables.
H ₄	Species Availability	Question 7 Vs Question 8	0.000	H4: There is a significant statistical difference between the variables.
H ₅	Non-toxic Material	Question 7 Vs Question 8	0.000	H5 There is a significant statistical difference between the variables.
H ₆	Aspect (color, smell)	Question 7 Vs Question 8	0.000	H6: There is a significant statistical difference between the variables.

The results showed there was a significant difference found between those respondents that had worked with TMW products for all questions. The perception of the architects on the technical and marking aspects of TMW was dependent on that architect having worked with TMW products in the past. Due to the statistical difference between the two groups their perceptions are discussed separately.

Table 16. Question three from Respondents that Do not Work TM Wood Products.

Response / TM wood factor	Not at all familiar		Not so familiar		Somewhat familiar		Very familiar		Extremely familiar		Total
	%	Count	%	Count	%	Count	%	Count	%	Count	
Strength	52%	64	11%	14	30%	38	5%	6	2%	2	124
Dimensional stability	52%	64	11%	14	28%	35	7%	9	2%	2	124
Product pricing	62%	77	22%	27	13%	16	2%	3	1%	1	124
Species availability	61%	75	24%	30	12%	15	2%	3	1%	1	124
Non-toxic material	53%	66	21%	26	21%	26	4%	5	1%	1	124
Aspect (color, smell)	54%	67	19%	24	20%	25	6%	7	1%	1	124

Table 16 shows that even architects who have not worked with TMW products had a slight knowledge of TMW factors, where between 1% to 2% were “Extremely familiar” with the factors. These respondents might still have been hesitant about the performance of the product and the characteristics of the product had not convinced them yet. The case is similar for the respondents that selected “Very familiar”, where 3% to 9% selected the response and had still not used the product. The respondents that selected “Somewhat familiar” were between 12% to 31% and were more familiar with the dimensional stability and strength aspect of TMW, which were the most well-known aspects of TMW. These respondents had a slight understanding or had learned “something” about TMW factors without having used it, and they were most familiar with strength and dimensional stability and less familiar with the species availability and product pricing. The respondents that selected “Not so familiar”, were 11% to 24%, and the factors with most familiarity were strength and dimensional stability, and most of the respondents did not have an idea of the pricing and the physical aspects of TMW. Lastly, the respondents that selected “Not at all familiar” with TMW factors were between 52% to 62%, where most of the respondents were not familiar with product pricing and species availability.

An interesting finding with the results obtained in Table 16 is that these were respondents who had not worked with TMW and these were respondents who were familiar with the characteristics of the product. This could be attributed to information already published, information on the internet, or slow marketing that producers had done in the past. These respondents, for some reason, had not worked with the products and the reasons for their decisions are not known.

Overall, there were many respondents who still did not know much about TMW, which may be the reason they did not work with TMW. Based on the respondents, 53% were “Not familiar” with the “non-toxic aspect” of TMW, and that could be used as a strong marketing factor. Producers and distributors should start educating their consumers about the benefits of having a non-toxic product. Providing more information regarding non-toxicity could start by working on an environmental platform, to capture consumers’ interest (Campbell et al., 2015). Product pricing should also be a good marketing attribute, since based on the results obtained by Gamache (2017), the cost of material related to TMW products is relatively low compared to tropical hardwoods, wood-plastic composites, naturally durable and pressure treated wood. According to a project partner, one of the main goals for them was to modify low-value species and make them look similar to walnut, since many of their customers were attracted to the brown to dark chocolate color provided by higher priced walnut.

Table 17. Question Three from Respondents that Works TM Wood Products.

TM Wood Factor	Not at all familiar		Not so familiar		Somewhat familiar		Very familiar		Extremely familiar		Total
Strength	0%	0	14%	3	68%	15	18%	4	0%	0	22
Dimensional stability	0%	0	9%	2	55%	12	36%	8	0%	0	22
Product pricing	5%	1	36%	8	41%	9	18%	4	0%	0	22
Species availability	5%	1	41%	9	36%	8	18%	4	0%	0	22
Non-toxic material	14%	3	23%	5	27%	6	32%	7	5%	1	22
Aspect (color, smell)	14%	3	9%	2	55%	12	14%	3	9%	2	22

Table 17 shows the results from the respondents that had worked with TMW products. The respondents that had worked with TMW showed that they still knew little about TMW, since only between 0% to 5% selected “Extremely familiar” with the factors. The respondents that selected “Extremely familiar”, only selected the non-toxic material aspect, and the rest of the factors were not selected by the respondents. The respondents who selected “Very familiar” with TMW factors were between 14% to 36%, and the most selected aspects were dimensional stability (36%) and the non-toxic aspect (32%). The respondents had the least familiarity with visual aspect (14%), product pricing (18%) and species availability (18%). The respondents that selected “Somewhat familiar” were between 27% to 68% and had more knowledge about the strength and dimensional stability aspects and less knowledge about the non-toxic aspect of TMW. There were also between 9% to 41% of respondents that selected “Not so familiar”, where the least familiar aspect was species availability (41%) and product pricing (36%). Lastly, the respondents that selected “Not so familiar” were between 0% to 14%, where most of the respondents were not familiar with the non-toxic material (14%), visual aspect (14%), species availability (5%) and product pricing (5%). The strength and dimensional stability had no responses, meaning that these respondents had at least an idea of the mechanical performance of TMW.

An interest finding was that there was a large portion of respondents who selected “Not at all familiar” and “Not so familiar” (5% - 41%) that were not familiar with the product. The gap between the familiarity levels could be filled by providing more information about the specifics of TMW. Factors such as product pricing, could be exploited since it is an economical alternative to other wood products (Gamache, 2017). Spreading information about TMW performance from each producer or distributor would also help to expand market share.

The fifth question was used to determine how many projects the respondents had been involved with using TMW products over the past five years. The results are

summarized in Figure 6. Most of the respondents (77%) said between 1-5 projects. There were approximately 10 respondents who had only worked with TMW products once or twice. This aids in understanding the reason many respondents lack familiarity with TMW products. Two of the respondents (9%) had worked on between 6-30 projects and only one respondent had worked on more than 31 projects (5%), the other 9% of the respondents specified that they were not sure. These results showed that respondents were still trying to use the material in their projects and future projects might help them get more familiarized with the product.

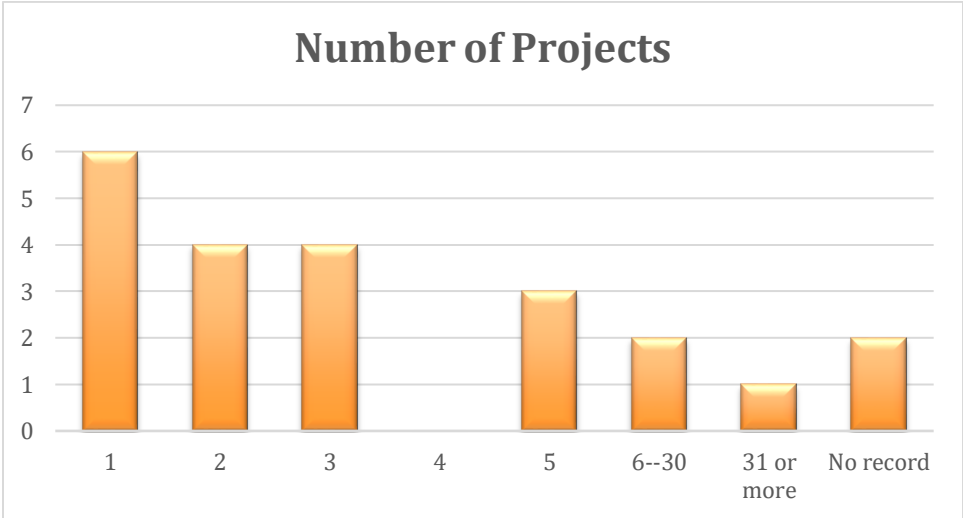


Figure 6. Target Audience Responses.

The sixth question was to determine where the respondents purchased the TMW from. Results showed 41% purchased it from a distributor and 41% selected “Other.” When the respondents specified, they said they purchased it from subcontractors. Another response obtained from the “Other” option, was that architects only specified the selection of the product, and their clients were the ones buying the product. The rest of the respondents (18%) answered they got the TMW directly from the manufacturer. These responses were an indication that distributors, manufacturers, and subcontractors could be the ones providing more information to their customers since they sell the product. The selection of “Other” also justified the lack of familiarity with TMW factors from the respondents in the third question, since around 41% of

the respondents mentioned that their customers were the ones selecting to work with TMW products.

The seventh question asked the architects about the technical aspects their clients were interested in when they specified working with TMW products and the responses are shown in Figure 5. This question allowed the respondent to select more than one option, which helped to understand what the top factors of interest were that could contribute to expanding the market share. Durability was chosen to be the most crucial aspect (26%) , followed by dimensional stability (18%) , eco-friendly (17%), visual aspects (16%), and strength performance (16%). According to Espinoza (2015) seven out of ten respondents (producers and distributors) selected that their most promoted attributes of TMW were durability and color, followed by “chemical-free, zero toxicity” (six out of ten) and dimensional stability (five out of ten), which were also the technical aspects the respondents (architects) were the most interested in. Understanding the physical aspects of TMW is beneficial for the product, but the information about mechanical performance is crucial for applications such as decking or flooring, where hardness and bending are important. This is an important issue for manufacturers and distributors to address by providing more information and advertising on the products, so customers can have a better understanding of the product, especially since it could be manufactured using different schedules.

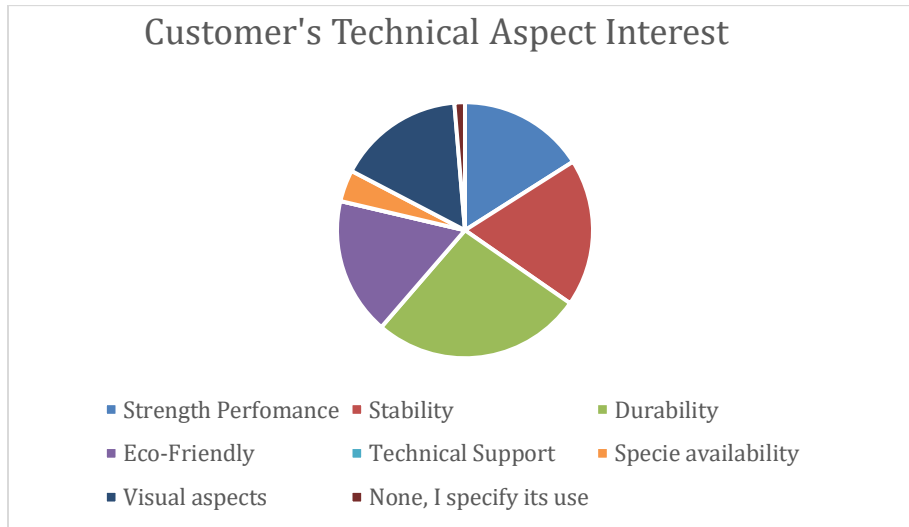


Figure 7. Important Technical Aspects (Question 7)

As shown in the Figure 7 the “technical support” aspect was not selected by a single respondent, then only one respondent selected “None, I specify its use”, which means that the client may have not heard of the product and the respondent (architect) made the recommendation. The other customer’s technical aspect with low interest was the ”species availability”, which could be attributed to the respondents not having been familiar with this factor (question 3).

The eighth question asked about marketing aspects their customers were interested in when they asked for TMW. Most of the respondents were interested in competitive prices (38%) and lead time delivery (24%) of the product. The interest in competitive prices was another factor that the respondents were not familiar with. Producers and distributors need to start providing more pricing information, since as mentioned by Gamache (2017), cost was an attribute that could boost the market share of TMW. The lead time delivery was also of high interest to respondents, since it could be crucial for them to have the product ready as soon as possible and could be the reason why producers currently have high levels of inventory. Inventory levels are discussed in the results of the third objective.

Obtaining TMW products from a local supplier could be of interest to the respondents (15%) since it would provide faster information about TMW and also contribute to the lead time delivery. Species availability was of low interest with only 9% of respondents interested in knowing which species were available with thermal modification. The respondents that selected “other” specified that they had interest in the “eco-friendly” aspect, which was covered in question 7. With customers not interested in the species available for the modification an opportunity could be created to stimulate the market for these low-value thermally modified species.

The ninth question asked the architects if they believed there was a lack of market awareness about TMW, and 91% of the respondents said “yes.” It is clear at this point that the market share of TMW needs to grow, and it has been shown there is a lack of knowledge that even among practitioners. It is important for the market and the architectural community that the producers start providing information on the performance of TMW, including the advantages and disadvantages, as well as the competitive prices the product has.

The tenth question asked about the intended applications that the customers were requesting when they worked with TMW products. Figure 8 shows the data and the interest they have in applications such as decking (32%), siding (30%), outdoor furniture (11%), and flooring (9%). The applications that they specified in the “Other” option (9%) were, sheds, pergolas, fencing, framing, and exterior trim. Respondents were using the product for the same purposes that were expressed in the literature review on section 2.2, which showed that the respondents understood the intended applications for the product. Question seven showed that there was an interest in knowing about physical aspects, durability, visual aspects, and strength performance. With the interest in these applications, it shows the importance of providing information about the mechanical aspects of TMW to the customers, due to interest in uses such as decking which is highly impacted by bending and hardness.

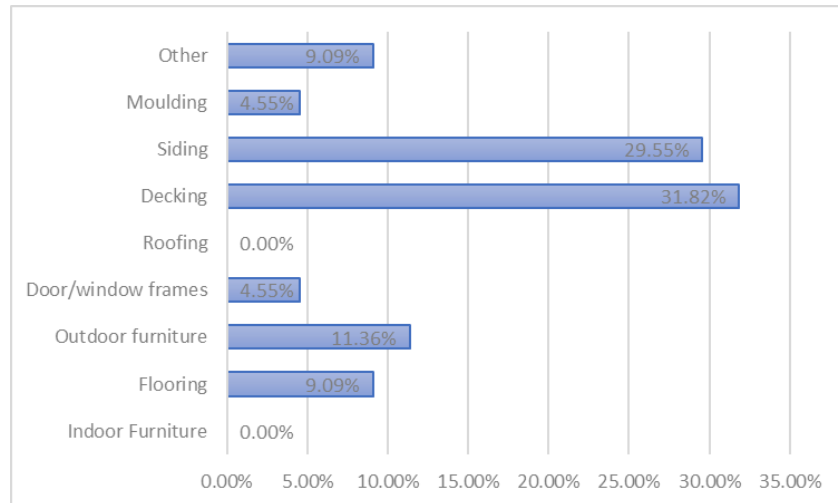


Figure 8. Intended Applications

The eleventh question asked about the species they were recommending to their customers. The purpose of this question was to determine which species were recommended by the respondents, since their opinion could potentially affect customer decision. Figure 9 shows the most common species used for TMW. Yellow poplar was the species that was recommended by most of the respondents (27%), then ash was the second most recommended species (22%). The “other” option had responses where they specified that they recommended species such as radiata pine, accoya, kebono, southern yellow pine, and cedar. Overall, this showed the high interest in species that are abundant in the east coast of the United States.

The twelfth question was similar but, in this case, asked their customers' perspectives on selecting a TMW species. The purpose of this question was to determine what the desired species were for the customer. Most of the respondents answered the option “Other,” where it was specified “they do not ask for any specific species or grade.” The second most popular option was “Ash,” with 24%, according to the respondents. This question highlighted the importance of the respondent (architect) in making the recommendation, since most of the time the species selection was determined by them. Also, it showed that ash was an attractive species for customers, and that manufacturers need to start promoting different species.

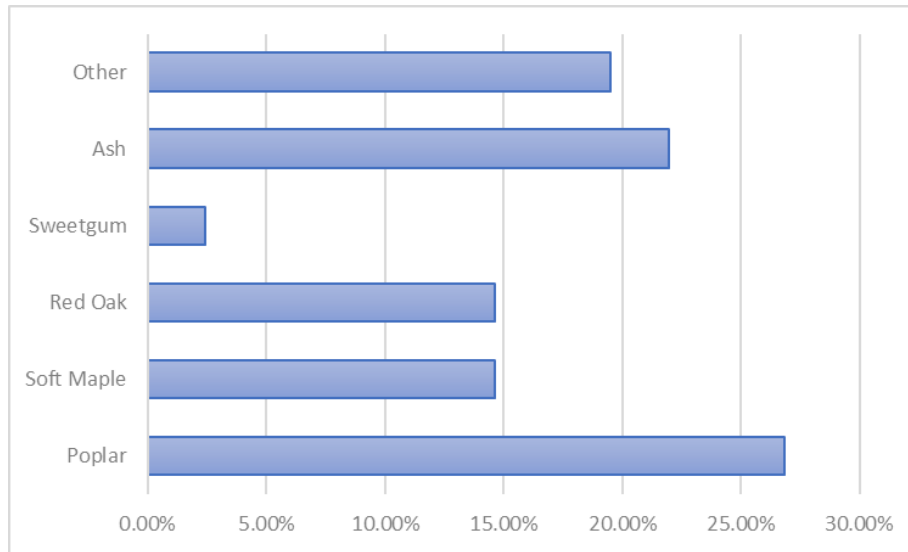


Figure 9. TM Wood Specie Recommended.

The thirteenth question asked if a project that had involved TMW was recommended by the architect or chosen by the customer, where 68% said the architect determined it, and 32% said it was the customer's desire to work with TMW. The reason to ask this question was to determine if the respondent's recommendation of the product was important. It highlighted that having a respondent with product information is crucial to expanding the market share, since, most of the time, the respondents were the ones making the recommendation. Also, this question could explain why there were respondents with low familiarity with the product who had already worked with the product.

The next three questions were open-ended. The fourteenth question asked which characteristics made them choose to work with TMW. Their interest in working with TMW was due to the longevity, installation, appearance (color), durability (decay resistance), dimensional stability, eco-friendliness, cost, and maintenance. Also, one of the answers was that were many municipalities/city halls/ institutions that were banning more common tropic hardwoods like Ipe. These results showcased, again, the importance of providing more information regarding the characteristics the respondents' customers were looking for, since TMW provides an alternative to the products with toxic substances or banned by municipalities (Freed et al., 2017).

Question fifteenth asked about the information the respondents would like to see regarding TMW, to potentially increase the market share. The respondents talked about the marketing aspects being weak, since there were respondents asking for TMW products and many local distributors did not know anything about the product. The respondents were interested in information regarding the long-term data on its average decay resistance, installation techniques, and environmental stability. Respondents were also interested in ways to maintain color, more information regarding prices, and specie availability. They not only wanted information regarding the good aspects of the product but also the disadvantages of TMW. They wanted availability of technical detailing requirements, performance metrics, and aesthetics choices. The respondents were also interested in an environmental product declaration, so they could rely on the environmental performance. Providing this information would boost the market share, with knowledge of more specifics of the product as well as future investigations on installation techniques, since this was also a concern for the partners of the project. A next step for manufacturers is to start providing information on proper installation techniques based on the schedules used, and to work with other producers to obtain an environmental product declaration.

The last question asked about other experiences or comments related to TMW they would be willing to share. Most of their concerns were about a lack of information regarding the market, product performance, and cost. This showed, again, the lack of information on the market and how information on technical and marketing aspects could expand the market share. Table 18 shows the comments from the last question.

Table 18. Final Comments on Survey

Comment
Availability and awareness both need to be greatly improved.
Needs more information to the market with lunch and learns for architects
Simply that the public is generally not aware of it
South Florida tough market area for product
I think it's a great product with a broad application for exterior construction, but I haven't been able to use it because it is expensive. We recently tried to spec it, but we had to change to conventional cedar to save money
Plan to use it more in the future.

It was shown in this section that there is still information that needs to reach the TMW audience (architects), and providing knowledge about the technical and marketing aspects would benefit the market share. Information on product pricing, installation techniques, disadvantages of TMW products, providing an environmental declaration for the product extolling the benefits for the environment are included in the information the respondents were looking for. Since the main sources of obtaining TMW are distributors and producers, it is up to them to start providing more information to their clients. Overall, there is potential to increase the market share of TMW, using current information by increasing the efforts made by the main distribution channels.

5.1.3 Wood Factors and Familiarity Relationships

The hypothesis established in section 4.1.1 is about the possible relationship between the business category and target audience with the familiarity of each TMW factor established in question 7 from the questionnaire. Table 19 shows a summary of the results obtained from the ordinal regression conducted for each hypothesis established. These hypotheses were established to determine if there was any relationship between the TMW factors studied and some of the demographics of the respondents.

With the results obtained from each ordinal logistic regression, every null hypothesis established was accepted, meaning that there was not a statistical association between the TMW factors and the business categories and target audiences. The only hypothesis where there was a statistical association was hypothesis 9, which studied the business category and product pricing familiarity.

Table 19. Results from the Ordinal Logistic Regression

Test	Questions	Hypothesis accepted	P-Value
Business Category vs. Strength Familiarity	Question 6 Vs Question 7	H ₇ : There is no statistical association between variables	0.877
Business Category vs. Dimensional Stability Familiarity	Question 6 Vs Question 7	H ₈ : There is no statistical association between variables	0.918
Business Category vs. Product Pricing Familiarity	Question 6 Vs Question 7	H₉: There is a statistical association between variables	0.017
Business Category vs. Species Availability Familiarity	Question 6 Vs Question 7	H ₁₀ : There is no statistical association between variables	0.492
Business Category vs. Non-Toxic Familiarity	Question 6 Vs Question 7	H ₁₁ : There is no statistical association between variables	0.836
Business Category vs. Aspect Familiarity	Question 6 Vs Question 7	H ₁₂ : There is no statistical association between variables	0.964
Target Audience vs. Strength Familiarity	Question 3 Vs Question 7	H ₁₃ : There is no statistical association between variables	0.803
Target Audience vs. Dimensional Stability Familiarity	Question 3 Vs Question 7	H ₁₄ : There is no statistical association between variables	0.664

Continuation Table 19

Test	Questions	Hypothesis accepted	P-Value
Target Audience vs. Product Pricing Familiarity	Question 3 Vs Question 7	H ₁₅ : There is no statistical association between variables	0.924
Target Audience vs. Species Availability Familiarity	Question 3 Vs Question 7	H ₁₆ : There is no statistical association between variables	0.759
Target Audience vs. Non- Toxic Familiarity	Question 3 Vs Question 7	H ₁₇ : There is no statistical association between variables	0.948
Target Audience vs. Aspect Familiarity	Question 3 Vs Question 7	H ₁₈ : There is no statistical association between variables	0.872

The results obtained from the ordinal logistic regression of the relationship between the business category and product pricing are displayed in Figure 8. “Architecture” is the reference level of the predictor since it is not shown in the Logistic Regression Table. Equation 6 shows the model used for the ordinal logistic regression.

$$y = construction(x_1) + contractors(x_2) + other(x_3) + b$$

Equation 6. Ordinal Logistic Regression Model.

In the Response Information Table, the first event is “1,” which stands for “Not so Familiar,” and the last event is “3,” which stands for “Very Familiar.” In the Logistic Regression Table, the most negative coefficient was the “Construction” predictor with -1.31814. Since it was the most negative, it meant that the respondents coming from the “Construction” category were more likely to respond, “Very Familiar.”

The logistic analysis provided the “Test that all slopes are zero,” where it considered all the coefficients from the predictors (business categories). This test determined

whether the association between the response events (pricing familiarity) and the predictors (Business categories) were statistically significant when the p-value was compared to the significance level; to assess the established null hypothesis. After performance OLR, it was concluded that there was not a statistical significance between the familiarity with strength, dimensional stability, species availability, or the non-toxic aspects, and the relationship to the business category or target audience. Meaning that there was no relationship if a respondent came from a specific business category and their familiarity with each TMW factor studied. It was the same for the target audience, there was not a relationship between the respondent's target audience and their familiarity with each TMW factor.

The only relationship found was between the business category and product pricing familiarity. According to the test of all slopes equal to zero shown in Figure 10, the p-value is 0.017, showing that there was a statistically significant association between the business category and the product pricing familiarity of TMW. The rest of the ordinal logistics regressions are in Appendix D.

Response Information

Variable	Value	Count
Pricing	1	196
	2	46
	3	12
	Total	254

Logistic Regression Table

Predictor	Coef	SE Coef	Z	P	Odds Ratio	95% CI	
						Lower	Upper
Const(1)	1.54485	0.195527	7.90	0.000			
Const(2)	3.37985	0.328538	10.29	0.000			
Business C							
Construction	-1.31814	0.557322	-2.37	0.018	0.27	0.09	0.80
Contractors	-0.907398	0.757593	-1.20	0.231	0.40	0.09	1.78
Other	-0.887491	0.348468	-2.55	0.011	0.41	0.21	0.82

Log-Likelihood = -160.957

Test of All Slopes Equal to Zero

DF	G	P-Value
3	10.158	0.017

Figure 10. Business category and Product Familiarity's Logistic Regression Table.

Since logistic regression considers all the coefficients for a categorical predictor, the Logistic Regression Table provided all the predictor's p-values, as shown in Figure 8. This p-value also determined whether the association between the product pricing familiarity and each business category was statistically significant. The p-value for "Construction" and "Other" were lower than the significance value (0.05), it showcased, again, that there was a statistical association for at least two of the business categories studied. Those who selected "Construction" and "Contractors" as a business category were more likely to choose "Very Familiar" with the product. The respondents that selected "Other" were more likely to respond, "Somewhat Familiar" and the "Architectural" were more likely to respond, "Not Familiar." The "Other" category had categories such as Landscaping Architecture and Interior Design. These results highlighted the importance of those respondents who came

from a construction and contractors business category and were more involved with the pricing of the product, compared to those respondents coming from an architectural business category.

These findings are supported by Espinoza (2015), where he concluded that the respondents' clients were not sensitive to prices, compared to mainstream markets, since the TMW products had competitive prices compared to tropical species, but less competitive compared to chemically-treated softwoods. Knowing this could explain the relationship between business categories and product pricing familiarity, due to the interest of some customers trying to work with products coming from tropical species or chemically treated species.

5.2 Objective 2: Industrial Variability.

This section summarizes the results of testing physical and mechanical properties to determine the variability of three different commercial operations for three species, yellow poplar (*Liriodendron tulipifera*), red maple (*Acer rubrum*), and ash (*Fraxinus americana*). The samples for testing were acquired from three commercial sources in North America. Testing samples from manufacturers and evaluating the performance variability between each manufacturer provided not only information on the current industry, but also created a baseline to standardize the expected performance of TMW. Each source used a different commercial system to thermally modify the wood. Company 2 used a closed system and company 1 used an open system to modify the wood. Company 3 was the only manufacturer that used both closed and open systems and, according to the experts in the company, they mentioned to have obtained better results from the closed system. The samples provided by company 3 were modified with the closed system. The schedules used for this sample were not provided by the company for proprietary reasons.

Tests on hardness, bending (MOE/MOR), and stability were conducted following ASTM D143 standards. Durability testing was conducted using AWWA E10 standards. The samples were conditioned at 20°C, at a relative humidity of 65% until they reached an equilibrium of moisture content before testing. ANOVA was then used to determine and compare the variability within and between each companies' processes. The alpha value to conduct each test was 0.05. Each company provided 14 samples from each species.

Before any analysis comparing the statistical differences between companies, a normality test was conducted. If the data did not fit the normal distribution, instead of an ANOVA, a non-parametric test known as the Kruskal-Wallis test was conducted. The results of the normality test are in Table 20. If the p-value obtained was lower than an alpha of 0.05, the data did not fit the normal distribution, and a Kruskal-Wallis test was conducted.

Table 20. Normality test for each species.

Specie	Test	P-value
Yellow Poplar	MOE	0.862
Yellow Poplar	MOR	0.315
Yellow Poplar	Hardness	0.374
Yellow Poplar	Radial Shrinkage	0.893
Yellow Poplar	Tangential Shrinkage	0.234
Yellow Poplar	EMC	0.893
Yellow Poplar	Gloeophyllum trabeum	0.000
Yellow Poplar	Trametes Versicolor	0.408
Red Maple	MOE	0.292
Red Maple	MOR	0.007
Red Maple	Hardness	0.356
Red Maple	Radial Shrinkage	0.006
Red Maple	Tangential Shrinkage	0.005
Red Maple	EMC	0.080
Red Maple	Gloeophyllum trabeum	0.000
Red Maple	Trametes Versicolor	0.060
Ash	MOE	0.649
Ash	MOR	0.231
Ash	Hardness	0.799
Ash	Radial Shrinkage	0.000
Ash	Tangential Shrinkage	0.280
Ash	EMC	0.085
Ash	Gloeophyllum trabeum	0.668
Ash	Trametes Versicolor	0.559

5.2.1 Static Bending (MOE/MOR)

5.2.1.1 Modulus of Elasticity (MOE)

Table 21 shows the MOE results obtained from the Analysis of Variance (ANOVA) for all the species studied. The results show a p-value of 0.762, 0,140 and 0.002, respectively. Based on the results obtained and hypotheses H2, H8, and H14 established in section 4.2, yellow poplar and red maple showed that the differences between the companies' mean for MOE were not statistically significant.

Table 21. Modulus of Elasticity Results.

Test	Specie	P-Value
MOE	Yellow Poplar	0.762
MOE	Red Maple	0.140
MOE	Ash	0.002

Since ash was the only specie that had a statistical difference in MOR between the three manufacturers, a graphical representation of the means and standard deviation for the test is shown in Figure 11. The interval plot displays that the mean value from company 1 was higher than the rest of the companies, and companies 2 and 3 shared means between them. These results also showed similar performance using the same system to thermally treat the wood, since the results were statistically the same for companies 2 and 3, and different compared to company 1, which used an open system. Having similar systems to modify wood could contribute to not having statistical differences, but also the schedules could have impacted these values. In this case, the system used to treat the wood did not have an effect, since company 1 and 3 used a closed system and the means are not shared, this could be attributed to the schedules utilized.

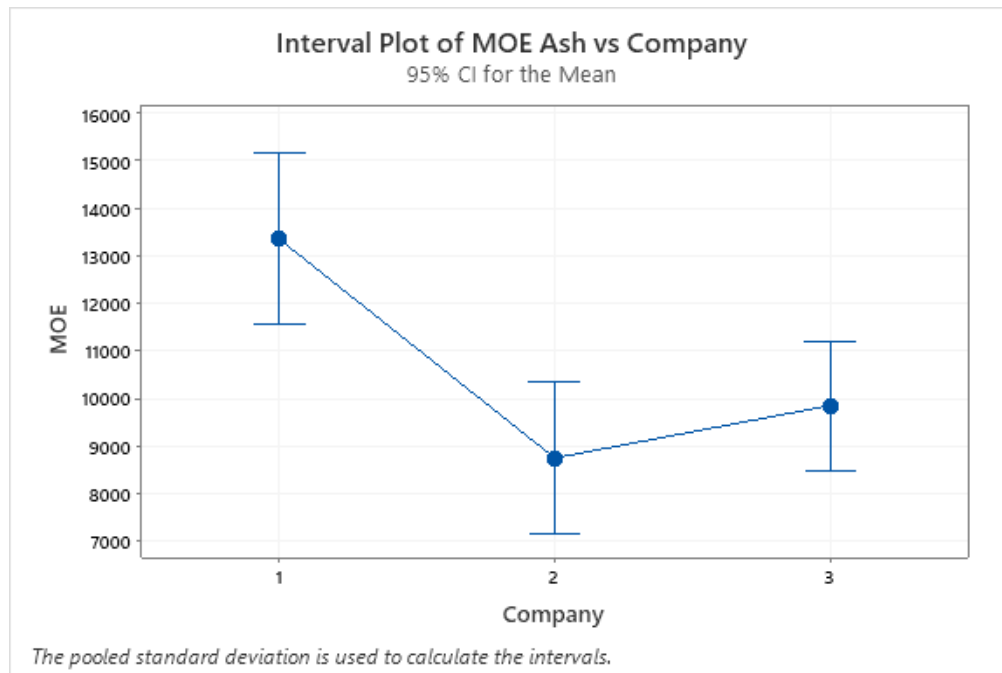


Figure 11. Interval Plot for the Ash MOE Values.

The standard deviation, mean, and median values are displayed in Table 22. The mean values were compared to heat treated values obtained for Calabrian pine and red maple showing a similar range with values between 8,034 – 13,584 MPa (Güntekin et al., 2017; Korkut et al., 2007).

Table 22. Descriptive Statistics for the MOE testing

Company	Specie	Test	Mean (MPa)	Std Dev	Median (MPa)
1	Yellow Poplar	MOE	12,502	2,287	12,710
2	Yellow Poplar	MOE	12,868	2,260	12,885
3	Yellow Poplar	MOE	12,229	2,323	12,025
1	Red Maple	MOE	13,260	874	13,271
2	Red Maple	MOE	13,733	2,876	13,376
3	Red Maple	MOE	14,646	1,022	14,727
1	Ash	MOE	13,336	2,719	13,971
2	Ash	MOE	8,740	2,004	9,336
3	Ash	MOE	9,844	2,649	10,118

The MOE value for untreated yellow poplar obtained from the literature was 10,900 MPa (Hill, 2007). The yellow poplar values from the samples from the three companies was higher. The incremental performance was 14%, 17%, and 12% for companies 1, 2, and 3, respectively. A similar trend occurred with red maple, where the MOE value for untreated red maple obtained from the literature was 11,300 MPa (Hill, 2007), compared to the ash values from companies 1, 2, and 3 which showed an incremental performance of 16%, 19%, and 26%, respectively. Finally, with ash, the MOE value for untreated ash obtained from the literature was 12,000 MPa (Hill, 2007). Compared to the ash values from company 2, it was 31% lower, and for company 3 it was 20% lower. Company 1 had an incremental performance compared to the untreated value of ash of 11%. This could have been influenced by the schedules used to treat the lumber, since the higher the conditions in the treatment the more it would have been affected (Esteves, 2009). The values obtained by Donahue (2011), using yellow poplar, reported a slight incremental value for MOE from 11,100 MPa to 12,258 MPa, which was similar to the values the author obtained in the results. Another factor to consider is that company 1 used an open

system to treat lumber, while company 2 used a close system, and 3 had both systems.

5.2.1.2 Modulus of Rupture (MOR)

Once the samples reached their maximum bending load, the MOR was estimated, answering hypotheses H1, H7, and H14 established in section 4.2. Table 23 shows the results obtained from the MOR testing from the three species studied. The p-values obtained were 0.164, 0.258*, and 0.124 for yellow poplar, red maple, and ash, respectively. The asterisk (*) means that the data was not normally distributed, and a Kruskal-Wallis test was conducted instead, testing the medians between the three companies. With the results obtained, the author concluded that the difference between the three companies studied for their MOR values was not statistically significant, meaning that the three companies had similar performance values for MOR. The systems used to thermally modify the wood might have not affected the MOR performance, since there was no statistical difference between the three companies.

Table 23. Modulus of Rupture Results

Test	Specie	P-Value
MOR	Yellow Poplar	0.164
MOR	Red Maple	0.258*
MOR	Ash	0.124

The standard deviation, the mean, and median values are displayed in Table 24. Results from Adewopo (2011) showed mean values between 107.60-140.53 for red oak, and between 81.51-110.66 for sweetgum, showcasing the lower performance for the three species treated in this study. The species treated by Adewopo used conditions between 93°C and 204°C, with treatment duration between 2-8 hours. These conditions could have contributed to the better performance obtained by Adewopo compared to the species in this study.

The best parameter to describe the data was the median, due to the data not fitting a normal distribution.

Table 24. Descriptive Statistics for MOR testing.

Company	Specie	Test	Mean (MPa)	Std Dev	Median (MPa)
1	Yellow Poplar	MOR	77.09	26.13	80.34
2	Yellow Poplar	MOR	81.2	18.63	83.68
3	Yellow Poplar	MOR	64.27	26.49	65.78
1	Red Maple	MOR	75.71	25.82	81.79
2	Red Maple	MOR	88.87	21.64	93.03
3	Red Maple	MOR	79.54	22.58	87.43
1	Ash	MOR	49.53	18.33	54.35
2	Ash	MOR	68.17	18.04	67.10
3	Ash	MOR	56.97	19.83	55.33

While the goal of this work was to compare the mechanical performance of the materials produced by the three companies, much of the literature on TMW focused on the difference in performance between TMW and untreated wood. Therefore, in this section 5.2.3, the author compared the MOR value for untreated yellow poplar obtained from Hill, 2007, 69.70 MPa, to the MOR values for TM yellow poplar from companies 1, 2, and 3. Material from companies 1 and 2 had greater MOR values than unmodified wood reported by Hill, 2007, 10% and 15%, respectively, and company 3 had an average MOR of 8%, less than Hill's (2007) reported value. In the case of red maple, the MOR value for untreated red maple obtained from the literature was 92.00 MPa (Hill, 2007), and the average value of MOR from companies 1, 2, and 3 showed a decrease in performance of 19%, 4%, and 15%, respectively. A similar trend happened with ash, where the MOR value for untreated ash obtained from the literature was 103.00 MPa (Hill, 2007), and the values from companies 1, 2, and 3, were 70%, 41% and 58% less, respectively. The values obtained by Donahue (2011) with yellow poplar reported a slight decremental performance for MOR from 103 MPa to 97 MPa, which were higher than the values the author obtained in these results. Literature generally supports that thermal modification results in either an increase or decrease and, given the mixed results between

species for this work, the author hypothesized that the differences noted were due to the different schedules used by each company for each species.

5.2.2 Hardness

The hardness test was conducted with samples of 1 by 2 by 6 inches, using a Janka ball test. The results are summarized in Table 25. An ANOVA was conducted to test for differences between the three companies, and the results showed that the yellow poplar and ash samples had no statistical difference between companies with p-values of 0.324 and 0.565, respectively.

Table 25. Hardness test Results

Test	Specie	P-Value
Hardness	Yellow Poplar	0.324
Hardness	Red Maple	0.007
Hardness	Ash	0.565

The red maple samples showed statistical differences between the average hardness values for the three companies. The results of a Tukey test are presented in Figure 12, where the plot shows that company 2 had higher hardness values compared to 1 (18%) and 3 (12%) and the mean values were shared between companies 1 and 3.

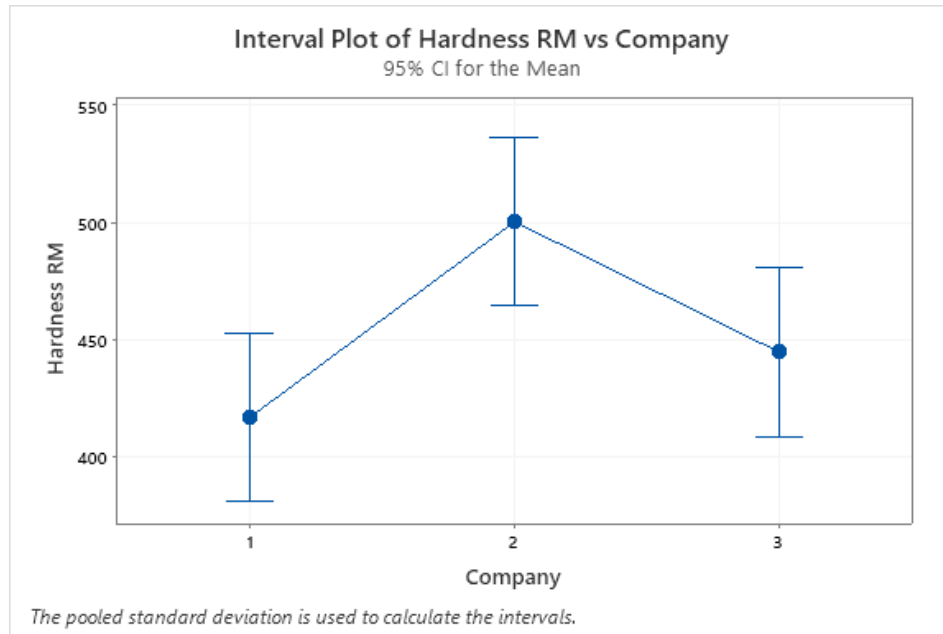


Figure 12. Interval Plot for Red Maple Hardness Values.

Table 26 shows the descriptive statistics from the hardness test, and the results show that the red maple hardness values tended to be lower, and even with high standard deviation values, the means were not shared between companies.

Table 26. Descriptive Statistics for the Hardness test.

Company	Specie	Test	Mean (kg)	Std Dev	Median (kg)
1	Yellow Poplar	Hardness	291.02	78.11	266.94
2	Yellow Poplar	Hardness	301.00	55.43	295.15
3	Yellow Poplar	Hardness	262.13	74.66	248.93
1	Red Maple	Hardness	416.76	67.09	425.02
2	Red Maple	Hardness	500.04	68.08	486.25
3	Red Maple	Hardness	444.52	63.73	430.82
1	Ash	Hardness	382.56	88.36	400.07
2	Ash	Hardness	400.02	64.05	386.82
3	Ash	Hardness	363.24	92.71	376.48

The hardness test conducted with red maple showed a significant statistical difference, where the values from company 2 were higher than the other two. The percentage of difference between company 2 and company 1 was 18% and between company 2 and 3 was 12%. The percentage of difference is the difference between

two positive numbers greater than 0, expressed as a percentage. The hardness values of TMW were expected to be lower based on research presented in the literature review, and could also be attributed to the technology used. These values are similar to untreated wood. The untreated hardness value for red maple obtained by Hill (2007) was 430.91 kg and compared to the values obtained from the results were close to each other with percentage differences between 3% -15%. This difference could have been due to the different schedules used and the use of different systems (closed and open) to treat the lumber. Comparing the results to the values obtained by Donahue (2011) showed a similar outcome, where the hardness values obtained by Donahue using yellow poplar and basswood at 200°C and 210°C, decreased to 420.93 kg and 354.71 kg for yellow poplar, respectively and for basswood 250.84 kg and 228.16 kg, respectively. The control value for basswood was 229.10 kg and for yellow poplar it was 615.07 kg.

5.2.3 Mechanical Test Results Compared to Literature

In total, there were nine tests conducted (three tests for three species). Four of them showed a decremental performance and five of them showed an incremental performance. Overall, there was an overall incremental increase in the mechanical properties, which could be attributed to the samples studied, treatments' temperature, treatments' duration, dimensions of the samples when they were treated, technology used, and/or type of system used.

Table 27 displays the average values of the mechanical properties from the three companies, and the untreated values for the same species from the literature. Since there were not t-pair samples to compare, this section made a comparison using representative population values from the literature (Hill, 2007). These representative population values were theoretical values that represented a population average. For example, the wood used to test yellow poplar came from several states across the country, and there is variability between the states to be considered.

Table 27. Mechanical values of treated and untreated wood species.

Test/Specie	MOE		MOR		Hardness	
	Mean (MPa)	Std Dev	Mean (MPa)	Std Dev	Mean (kg)	Std Dev
TM Yellow Poplar	12,640.07	(2,485.46)	74.92	(24.64)	278.26	(72.50)
Untreated Poplar	*10,900.00	--	*69.70	--	*244.94	--
TM Ash	11,114.08	(3,124.72)	51.99	(21.81)	370.97	(90.60)
Untreated Ash	*12,000.00	--	*103.00	--	*601.64	--
TM Red Maple	13,787.89	(1,958.14)	80.13	(24.07)	449.82	(82.24)
Untreated Maple	*11,300.00	--	*92.00	--	*430.91	--

*Source: (Hill 2007)

The MOE values showed an incremental value for yellow poplar and red maple compared to untreated values of 15% and 20%, respectively, and ash showed a decrease of 8%. Similar results occurred with the hardness values, where yellow poplar and red maple showed better performance, compared to untreated values, of 13% and 4%, respectively. The performance of ash showed a decrease of 47%. As for MOR, it showed a decremental performance in ash and red maple of 66% and 14%, respectively, and better performance in yellow poplar, compared to untreated values, of 7%.

The average MOE measured for all three companies was higher than the average MOE of untreated wood as measured by Hill (2007). This was not expected, since most literature described a decrease in mechanical performance (Esteves et al., 2008). Also, most of the work studied by Esteves did not specify the technology used to thermally modify the wood, only the schedule utilized. This is crucial, since the technology utilized by manufacturers might be different. Candelier (2014) mentioned that commercial technologies utilizing a vacuum in their systems did not see a considerable reduction of the mechanical properties of wood after the modification, due to improved drying of the wood in the chamber.

With different schedules and technologies to produce TMW, it makes sense to have different values such as an incremental increase in MOE, MOR, and hardness performance, depending on the specie. Also, the partners of the project said that they were still in the learning process to figure out the best schedules for each species they treated.

As mentioned before, the mechanical properties were expected to decrease after thermal modification, due to the degradation of hemicelluloses (Winandy et al., 2001, Esteves et al., 2008B). Table 28 displays results obtained from several authors studying different thermally treated species.

Table 28. Mechanical Results from Different Studies

Specie	Test	Treated	Untreated	Time (Hrs.)	Temperature(°C)
Norway spruce	MOE	11,225 (MPa)	10,669 (MPa)	6	180
Scots pine	MOE	10,660 (MPa)	9,660 (MPa)	6	180
Eucalyptus	MOE	27,646 (MPa)	15,974 (MPa)	3	180
Açoita-cavalo	MOE	8,443 (MPa)	8,462 (MPa)	2	180
Norway spruce	MOR	57.2 (MPa)	39.3 (MPa)	6	180
Scots pine	MOR	85.9 (MPa)	88.7 (MPa)	6	180
Açoita-cavalo	MOR	63.04 (MPa)	81.77 (MPa)	2	200
Red oak	Hardness	391.42 (Kg)	672.00 (Kg)	6	190
Yellow Poplar	Hardness	363.00 (Kg)	335.00 (Kg)	6	190
Black Alder	Hardness	332.00 (Kg)	342.00 (Kg)	6	190

Source: Santos, 2000; Boonstra et al., (2007); Schneid, (2014); Salca et al., (2014).

The MOE results showed that the thermally modified samples from different species had an incremental effect on the bending properties, compared to untreated values. This might have been due to the technology, treatment schedules, or species used, but the results were similar to results from this study. In the case of MOR, the results also varied between species, where some species showed an incremental change in performance compared to untreated values. For Açoita-cavalo, the performance decreased. Lastly, the hardness results showed an incremental change in red oak and yellow poplar which was also shown in this study, but in the case of black alder the performance decreased. These results showed that treatment conditions

affected the performance of TMW, and that similar species perform similar to each other.

5.2.4 Equilibrium of Moisture Content (EMC)

The results from testing what the EMC would be at 21°C and 65% relative humidity (RH) indicated that there was a difference between the companies for the three species studied. The results are summarized in Table 29.

Table 29. EMC test Results

Test	Specie	P-Value
EMC	Yellow Poplar	0.000
EMC	Red Maple	0.000
EMC	Ash	0.000

Figures 13, 14, and 15 show the interval plot that the Tukey test provides. The plots display the confidence intervals for each mean. These confidence intervals show that none of the EMC values obtained share means between the companies for any of the species studied.

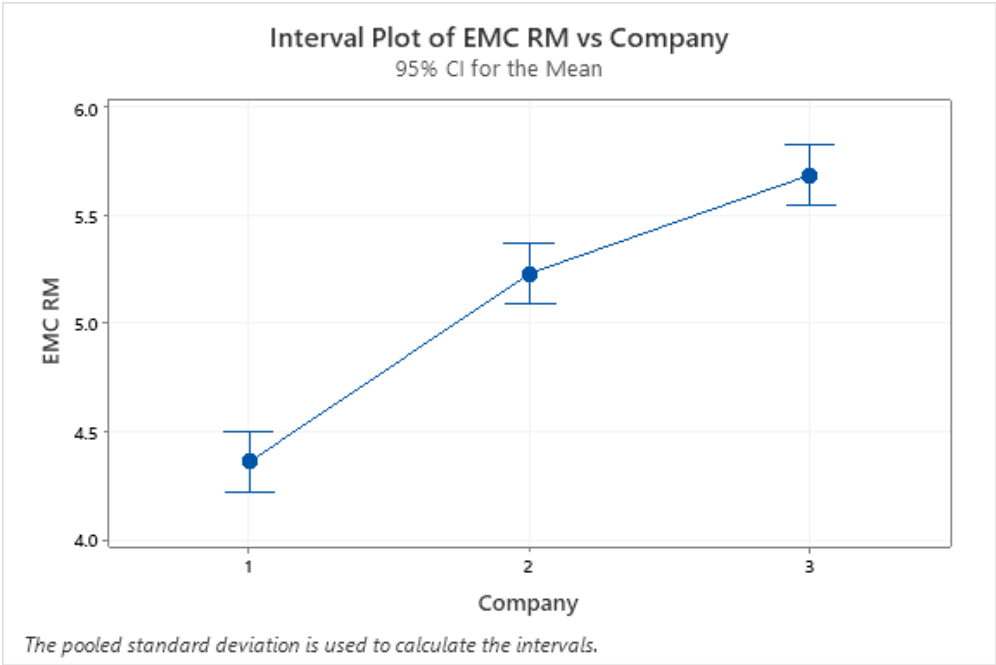


Figure 13. Interval Plot for Red Maple EMC Values.

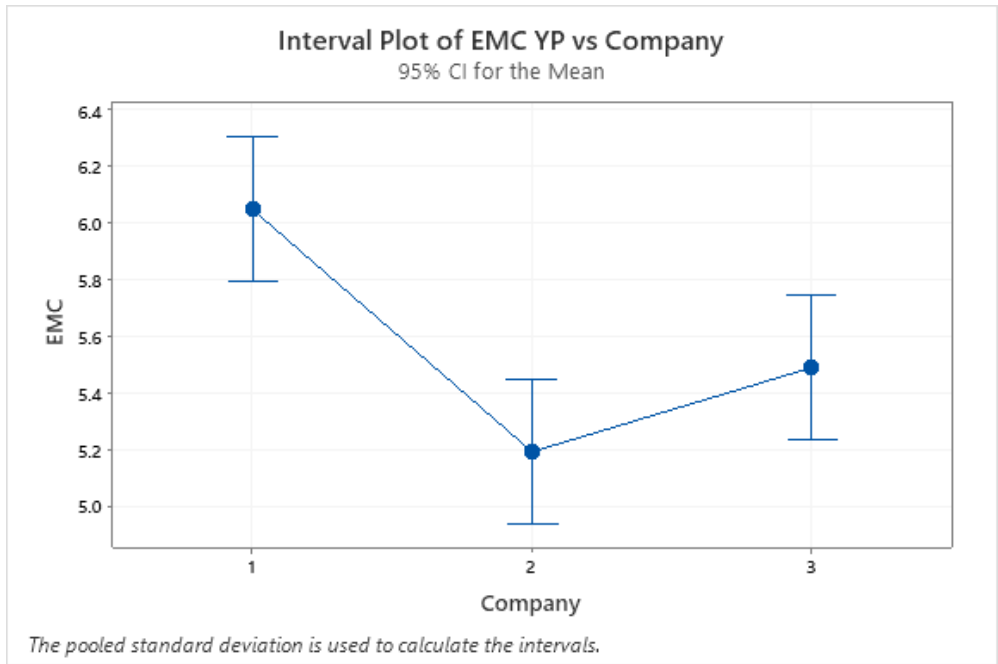


Figure 14. Interval Plot for Yellow Poplar EMC Values.

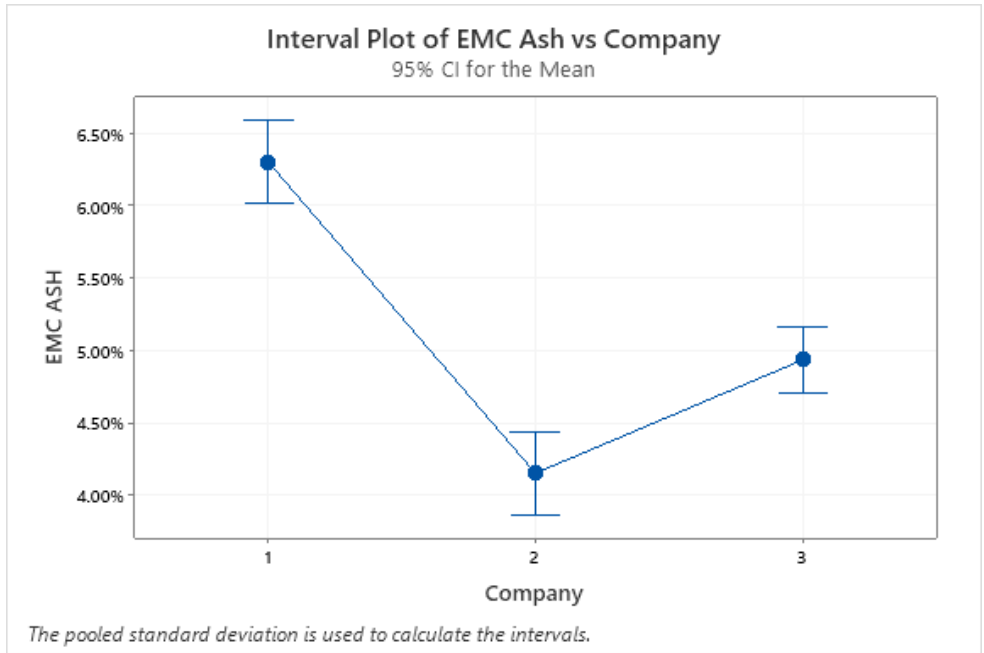


Figure 15. Interval Plot for Ash EMC Values.

The descriptive statistics are displayed in Table 30, where the mean values are between 4-6% of EMC with low standard deviation values.

Table 30. Descriptive Statistics for the EMC test.

Company	Specie	Test	Mean (%)	Std Dev	Median (%)
1	Yellow Poplar	EMC	6.046	0.529	6.159
2	Yellow Poplar	EMC	5.191	0.543	5.234
3	Yellow Poplar	EMC	5.488	0.302	5.496
1	Red Maple	EMC	4.360	0.194	4.317
2	Red Maple	EMC	5.232	0.207	5.185
3	Red Maple	EMC	5.688	0.343	5.630
1	Ash	EMC	6.303	0.700	6.200
2	Ash	EMC	4.151	0.350	4.001
3	Ash	EMC	4.934	0.228	4.930

The EMC values from the three companies for each wood species studied were statistically significant. The percentage of difference between the average EMC values for yellow poplar between companies 2 and 1 it was 15 % and for companies 1 and 3 it was 10%. For red maple, the percentage of difference between companies 2 and 1 was 18%, and for companies 1 and 3 it was 26%. For ash, the percentage of difference between companies 2 and 1 was 41%, and between 1 and 3 it was 17%.

Overall, the EMC values obtained were close to each other in relation to their difference to untreated wood, since the range of the results was between 5 - 6%. , This showed, again, that companies 2 and 3 tended to have similar values, which were different compared to company 1. As explained in the literature, in a closed system's centrifuge the steam stays in the chamber, which creates pressure. An open system reduces the moisture content to 0% and eliminates steam from the chamber and then reinjects the steam to condition the wood.

These results showed small differences first, due to the low variability between the samples and how similar the results were for each company, but also due to the different schedules used by the companies for each specie. In treatments with high exposure time and temperature, the EMC tended to decrease, as was mentioned in section 2.2.5.1 of the literature review.

5.2.5 Dimensional Stability

Dimensional stability at conditions of 21°C and 65% RH for radial and tangential planes of reference was determined using ASTM D143. The results are displayed in Table 31, where the values with asterisks did not meet the normality to conduct an ANOVA, instead a Kruss-Kal Wallis test was used. The shrinkage for the tangential sections of yellow poplar had no statistical differences but the red maple and ash samples had statistical differences between the companies studied.

For the radial section, the three species had p-values with values greater than 0.05, meaning that there were no statistical differences between companies.

Table 31. Dimensional stability test results

Test	Specie	P-Value
Shrinkage-Tangential	Yellow Poplar	0.356
Shrinkage-Tangential	Red Maple	0.002*
Shrinkage-Tangential	Ash	0.034
Shrinkage-Radial	Yellow Poplar	0.178
Shrinkage-Radial	Red Maple	0.299*
Shrinkage-Radial	Ash	0.922*

Figure 16 A shows the results from the Tukey test for red maple. The means were shared between two of the companies, where company 3 had higher tangential shrinkage values compared to companies 1 and 2.

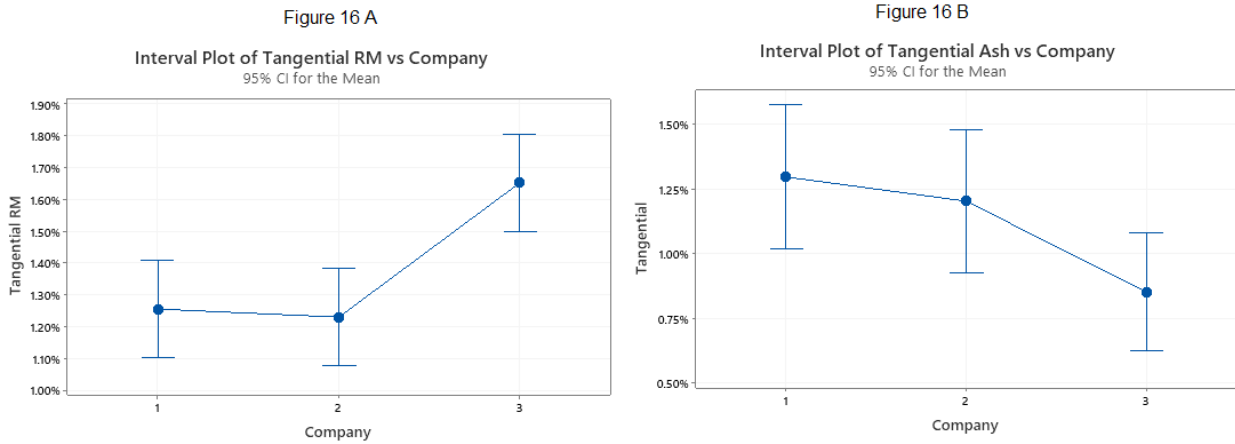


Figure 16. Tukey test for Red Maple Shrinkage Results

Figure 16 B displays the Tukey analysis for the tangential section of ash. The results showed that company 1 had higher shrinkage values compared to the other two companies, and means were shared between companies 1 and 2. Table 32 also shows the descriptive statistics for the dimensional stability test. The results showed low standard deviation values and similar values between the mean and the median.

Table 32. Descriptive Statistics for the dimensional stability test.

Company	Specie	Test	Mean (%)	Std Dev	Median (%)
1	Yellow Poplar	Radial Shrinkage	1.21	0.33	1.24
2	Yellow Poplar	Radial Shrinkage	1.07	0.19	1.05
3	Yellow Poplar	Radial Shrinkage	1.01	0.33	1.05
1	Red Maple	Radial Shrinkage	1.02	0.28	1.05
2	Red Maple	Radial Shrinkage	0.93	0.33	0.96
3	Red Maple	Radial Shrinkage	1.17	0.33	1.02
1	Ash	Radial Shrinkage	1.11	0.63	0.97
2	Ash	Radial Shrinkage	0.87	0.30	0.78
3	Ash	Radial Shrinkage	0.97	0.59	0.73
1	Yellow Poplar	Tangential Shrinkage	1.27	0.40	1.20
2	Yellow Poplar	Tangential Shrinkage	1.08	0.10	1.10
3	Yellow Poplar	Tangential Shrinkage	1.22	0.40	1.20
1	Red Maple	Tangential Shrinkage	1.26	0.30	1.10
2	Red Maple	Tangential Shrinkage	1.22	0.20	1.10
3	Red Maple	Tangential Shrinkage	1.65	0.30	1.70
1	Ash	Tangential Shrinkage	1.30	0.58	1.32
2	Ash	Tangential Shrinkage	1.20	0.21	1.19
3	Ash	Tangential Shrinkage	0.85	0.42	0.86

Overall, two of the six tests conducted showed statistical differences and the remainder showed no statistical differences, meaning the companies had similar results regarding dimensional stability performance. As mentioned in the literature review in section 2.2.5.2, dimensional stability is improved due to the decrease of equilibrium of moisture content, mainly due to the decrease of wood hygroscopicity affected by high temperatures (Dirol et al., 1993).

The dimensional stability for the tangential surface showed statistical differences for red maple and ash. The percentage of difference of the tangential surface of red maple between companies 1 and 2 was 30%, and between companies 1 and 3 it was 27%. The percentage of difference for ash in the tangential surface between companies 2 and 3 was 34%, and between companies 2 and 3 was 42%. For the ash values, the percentage of difference was more prominent, but when the values were compared to untreated values, the performance was better. These improvements are discussed in the next section.

5.2.6 Physical Test Results Compared to Literature.

As mentioned by Esteves (2009), the major improvement in TMW was the decrease of equilibrium of moisture content, which leads to improved dimensional stability. This improvement was dependent on wood species, temperature, and time. Table 33 displays the average values from the physical properties conducted from the three companies, and untreated values of shrinkage for the same species studied from the literature.

Table 33. Treated and Untreated values from Physical test.

Test/Specie	EMC		Radial		Tangential	
	Mean (%)	Std Dev	Mean (%)	Std Dev	Mean (%)	Std Dev
TM Yellow Poplar	5	(0.54)	1	(0.31)	1	(0.36)
Untreated Poplar	12**	--	*5	--	*8	--
TM Ash	5	(0.83)	1	(0.60)	1	(0.53)
Untreated Ash	12**	--	*5	--	*7	--
TM Red Maple	5	(0.63)	1	(0.58)	1	(0.34)
Untreated Maple	12**	--	*4	--	*8	--

*Source: Hill (2007); ** Hailwood (1946)

Overall, the results obtained from the physical tests, showed improved values of 5% to 1%, for the radial section for yellow poplar with treated and untreated values, and for the tangential section the red maple samples showed untreated and treated values from 8% to 1%. In the case of EMC, the values improved approximately from 12% to 5%. There were differences in the values between the companies, as shown in the previous section, but each showed larger reductions, relative to untreated values. While there were statistical differences between for the values of some of the companies, the overall improvements, compared to untreated wood, were quite large, from 12% to 5%. This demonstrated that, relative to untreated wood, the different commercial processes were a significant improvement.

5.2.7 Durability

The durability test was conducted using the AWPA E10 standard, which evaluates the resistance of wood to decay by selected species of fungi. The selected fungi species evaluated were; “Gloeophyllum trabeum” and “Trametes versicolor.” This test was conducted for the three companies using the three species selected for the project. However, Ash samples from company 2 were not evaluated as they were not able to provide any samples.

Table 34 displays the results. The values with a double asterisk only compare two of the three companies studied (1 and 3). The three wood species treated with the

two fungi showed no statistical differences, thus there were no differences in the durability for each species between the companies.

Table 34. Durability test results

Test	Specie	P-Value
Durability-Gloeophyllum trabeum	Yellow Poplar	0.162
Durability-Gloeophyllum trabeum	Red Maple	0.505
Durability-Gloeophyllum trabeum	Ash	0.529**
Durability-Trametes Versicolor	Yellow Poplar	0.145
Durability-Trametes Versicolor	Red Maple	0.388
Durability-Trametes Versicolor	Ash	0.175**

Table 35 shows the descriptive statistics for the durability tests. The standard deviation values are high, but the results were as expected, due to similar results obtained from different authors with different species studied (Larose (2014); Schirp et al., (2007); Sivrikaya et al., (2015); Anagnost et al., (1997)).

Table 35. Descriptive Statistics for the durability test.

Company	Specie	Test	Mean (%)	Std Dev	Median (%)
1	Yellow Poplar	Durability-Gloeophyllum	3.540	4.170	2.190
2	Yellow Poplar	Durability-Gloeophyllum	1.168	0.696	1.538
3	Yellow Poplar	Durability-Gloeophyllum	1.536	0.715	1.132
1	Red Maple	Durability-Gloeophyllum	1.482	0.709	1.687
2	Red Maple	Durability-Gloeophyllum	1.329	0.590	1.575
3	Red Maple	Durability-Gloeophyllum	1.967	1.489	1.478
1	Ash	Durability-Gloeophyllum	1.129	0.617	1.055
2	Ash	Durability-Gloeophyllum	1.151	0.428	1.205
1	Yellow Poplar	Durability-Trametes	1.919	0.399	1.835
2	Yellow Poplar	Durability-Trametes	1.668	0.560	1.374
3	Yellow Poplar	Durability-Trametes	1.718	0.379	1.899
1	Red Maple	Durability-Trametes	1.261	0.614	1.096
2	Red Maple	Durability-Trametes	0.900	0.644	1.139
3	Red Maple	Durability-Trametes	1.011	0.397	0.893
1	Ash	Durability-Trametes	0.960	0.424	1.023
2	Ash	Durability-Trametes	0.615	0.345	0.613

The durability results for the company 1, when testing yellow poplar with *Gloeophyllum trabeum*, showed a standard deviation value higher than the mean

values. This was due to a sample presenting massive weight loss and the rest of the values presenting minimal weight loss values. But each company presented same mean values compared to each other.

Table 36 shows the average values from the durability test from the three companies, and untreated values for the same species studied in the literature.

Table 36. Durability values of treated and untreated wood species.

Test/Specie	G. trabeum Average Mass Loss (%)	T. versicolor Average Mass Loss (%)
TM Yellow Poplar	2	2
Untreated Poplar	27*	62**
TM Ash	1	1
Untreated Ash	12*	45***
TM Red Maple	2	1
Untreated Maple	10*	--

Source: * Larose (2014); ** Schirp et al., (2007); *** Sivrikaya et al., (2015); Anagnost et al., (1997)

As expected, the average values of the three companies showed an improvement in the decay resistance of TMW, when compared to untreated wood. Some thermally modified yellow poplar treated by Shi (2007), showed improvements from untreated values of 69% of weight loss to 18%. Literature indicated that thermal modification increased the performance against brown-rot more so than white-rot (Esteves, 2009; Sandberg et al., 2015), and the obtained results demonstrated this. Most importantly, the results showed that different commercial processes and schedules resulted in the same decay resistance for all three species tested.

The results of mechanical testing determined the variability across different mechanical and physical tests, where even with a statistical difference for some tests, the behavior of the results were similar between the companies studied. Table 37 summarizes the results from this section. The Tables show the hypothesis with the p-value obtained from each test conducted.

Table 37. Test Results Summary

Test	Hypothesis accepted	P-Value
Yellow Poplar- MOR	H1: $\mu_1 = \mu_2 = \mu_3$	0.164
Yellow Poplar- MOE	H2: $\mu_1 = \mu_2 = \mu_3$	0.762
Yellow Poplar- Radial S	H3: $\mu_1 = \mu_2 = \mu_3$	0.178
Yellow Poplar- Tangential S	H4: $\mu_1 = \mu_2 = \mu_3$	0.356
Yellow Poplar- Hardness	H5: $\mu_1 = \mu_2 = \mu_3$	0.324
Yellow Poplar- EMC	H6: At least one mean is different	0.000
Yellow Poplar- Durability: Gt	H7: $\mu_1 = \mu_2 = \mu_3$	0.162
Yellow Poplar- Durability: Tv	H8: $\mu_1 = \mu_2 = \mu_3$	0.145
Red Maple – MOR	H9: $\mu_1 = \mu_2 = \mu_3$	0.258
Red Maple - MOE	H10: $\mu_1 = \mu_2 = \mu_3$	0.140
Red Maple - Radial S	H11: $\mu_1 = \mu_2 = \mu_3$	0.299
Red Maple - Tangential S	H12: At least one median is different	0.002
Red Maple - Hardness	H13: At least one mean is different	0.007
Red Maple - EMC	H14: At least one mean is different	0.000
Red Maple – Durability: Gt	H15: $\mu_1 = \mu_2 = \mu_3$	0.505
Red Maple – Durability: Tv	H16: $\mu_1 = \mu_2 = \mu_3$	0.388
Ash – MOR	H17: $\mu_1 = \mu_2 = \mu_3$	0.124
Ash - MOE	H18: At least one mean is different	0.002
Ash - Radial S	H19: $\mu_1 = \mu_2 = \mu_3$	0.922
Ash - Tangential S	H20: At least one mean is different	0.034
Ash - Hardness	H21: $\mu_1 = \mu_2 = \mu_3$	0.565
Ash - EMC	H22: At least one mean is different	0.000
Ash – Durability: Gt	H23: $\mu_1 = \mu_2 = \mu_3$	0.529
Ash – Durability: Tv	H24: $\mu_1 = \mu_2 = \mu_3$	0.175

The results from the study showed that 7 out of 24 (29%) tests conducted indicated that the three commercial processes had statistical differences regarding their mechanical and physical performances. The rest of them did not show statistical differences regarding the mechanical and physical performance of yellow poplar, red

maple, and ash. Additionally, the results highlighted that the commercial processes had different schedules and technologies to thermally modify the wood. These schedules might vary between species and dimensions from each company, as was covered in the results section for the third objective. Seventy-one percent of the tests conducted showed that the performance was similar between companies.

There was a high likelihood of getting a different product from different companies since these companies used different schedules and had different production systems, but the performance between companies were still close to each other. From an application perspective, the statistical differences, schedules, and systems used were not important, since there was an incremental increase in dimensional stability, durability, and EMC performance. The yellow poplar samples showed little difference between the companies. The only difference was in the EMC values, with similar values of 5% to 6%. This was evidence that consumers (architects) could get yellow poplar from any producer and expect similar performance any differenced being so small in actuality that they would not be noticeable. The red maple samples showed statistical differences. Company 2 had a better hardness performance value, meaning that their product was better for flooring applications, and company 3 showed better performance for dimensional stability, which was better for siding applications. Regarding durability and static bending performance, red maple was not different from company to company. The ash samples showed that the MOE values for company 1 were higher, which was better for decking applications. The dimensional stability was the same for companies 1 and 2, and for company 3 the performance was lower for the tangential section. The performance of ash from the three companies was similar from a practical perspective, since there were still improvements for the properties most of the consumers were looking for, as mentioned in the survey results from section 5.1.2. The improvements for EMC values went from 12% of MC to 5% for the three species, the radial shrinkage went from values around 5% to 1% and same case for the tangential shrinkage with values from between 7% and 8% to improved values to 1%. The durability performance was

also showed good performing values with performances between 1% to 2% of weight loss percentage.

As demonstrated by the performance obtained from each specie and company, and the commercial processes obtained from the companies studied, TMW is starting to settle into a performance baseline within the industry. Producers are figuring out the optimal schedules and practices for TMW. The next section of this study focuses on the production process of TMW to better understand the practices of these companies.

5.3 Objective 3: Lean Process Strategy.

This section starts with the use of a value stream map to provide a description of the process used by each of the three companies, followed by a discussion of how opportunities for improvement were determined, and finally the development and presentation of the ideal value stream map.

Lean is recognized for saving time, money, and resources while reducing waste and increasing value. For an appropriate performance of Lean thinking, the workforce must understand why change is necessary. Even though Lean thinking has been successful in many industries the current practices producing TMW products have not explored opportunities to reduce waste in their processes.

There were two types of machines used by the participating companies. The first machine employed an open system, and the second type used a closed system. An open system refers to a process where the moisture contained in the wood is released, allowing the material to go all the way down to 0% moisture content, while the steam exits the chamber. Once the temperature cycle is done, the steam is reinjected into the process to condition the wood. Unlike the open system, the closed system maintains the released steam in the chamber and creates pressure. This means that the moisture stays in the wood during the process and should be

monitored appropriately to prevent boiling of the moisture inside, which would cause splitting and cracking in the final product. The companies studied had an activity that all them referred as “Conditioning”, which was a “cooling down” process to handle the lumber until it reached room temperature. The “stacking” activity was another process used by the three companies which involved adding small sticks of wood between boards. This study focused on the general perspective, not on specie or thickness.

The unit of measurement for hardwood lumber is in Board Feet (BF), Equation 7 shows the unit of measurement for hardwood lumber.

One board foot us is:

$$1 \text{ foot long} \times 1 \text{ foot wide} \times 1 \text{ inch thick}$$

Equation 7. Board feet.

And the Equation 8 for determining board feet in a board is:

$$\frac{(\text{Width in inches}) \times (\text{lenght in feet}) \times (\text{thickness in inches})}{12}$$

Equation 8. Board feet estimation.

5.3.1 Process Description and Mapping

This study involved three companies, which were the primary sources of visual data. They allowed observation of their manufacturing processes and provided information regarding all the steps necessary to produce TMW.

At the time of the study, Company 1 employed 60 workers, company 2 had 30 workers, and Company 3 had 150 workers at their facilities.

Companies 1, 2, and 3 offered a variety of wood species for thermal modification with different final applications. Their catalog of wood types and possible uses are shown in Table 38.

Table 38. Catalog of Wood species for thermally modified wood and final application of each company

Catalog	Company 1	Company 2	Company 3
Available Wood species	<ul style="list-style-type: none"> • Poplar • Ash • Sweet Gum • Red Oak • White Oak • Red Grandis • Soft Maple • Cypress • Eastern White Pine • Southern Yellow Pine 	<ul style="list-style-type: none"> • Yellow Poplar • White Ash • Red Oak • Soft Maple 	<ul style="list-style-type: none"> • Poplar • Soft Maple • Red Oak • White Ash • White Oak
Applications	<ul style="list-style-type: none"> • Siding/ Cladding • Decking • Rainscreen Systems • Outdoor Furniture • Window Framing • Porch Flooring • Shutter • Doors • Flooring • Custom Bathroom Features • Furniture 	<ul style="list-style-type: none"> • Siding • Architectural millwork • Cabinetry • Furniture • Flooring • Paneling • Trim • Musical instruments 	<ul style="list-style-type: none"> • Siding • Decking • Porch Flooring • Decorative trim and mouldings

Source: Company 1, 2, and 3.

Each company had different export markets. Company 1 exported 5% of the total sales of the company, company 2 approximately 10%, and company 3 also approximately 10%. The export numbers showed that the overwhelming majority of the market for TMW was in the domestic market. This supported focusing on understanding the domestic market and how to improve market share in the domestic market. Table 39 shows the export markets reported for each organization.

Table 39. Markets for companies 1, 2, and 3.

Company 1	Company 2	Company 3
<ul style="list-style-type: none"> • Asia • Europe • USA 	<ul style="list-style-type: none"> • Australia • Japan • United Kingdom • USA 	<ul style="list-style-type: none"> • International (not specified) • USA

Source: Companies 1, 2, and 3

Each company production process is detailed separately in the following section.

5.3.1.1 Company 1

The data required for the VSM analysis was collected during a single visit to the manufacturing plant, guided by the company's president. An interview with the president and vice president of the company was conducted to obtain their process information. Direct observation was used at the facility to understand the process flow.

5.3.1.1.1 Prior to the Thermally Modified Wood Process

The production of TMW starts with kiln-dried wood in the form of sawn lumber. Lumber comes from a sawmill with a 60 to 80 moisture content, which is reduced in a dry kiln, where the time required for drying is dependent on the species and thickness of the material. The lumber comes from 35 to 40 different sawmills in approximately a 200-mile radius. The facilities visited had 350 thousand ft of conventional kiln capacity. Some species were air-dried prior to kiln drying. A dry kiln is used to control the humidity, heat, and airflow to lower the moisture content to 6% to 8%. At the time of the study, the companies were drying around 1 million board feet of wood per month. After the material was dried to the desired moisture content, it was then regraded and sent to either the warehouse, shipped to customers, went to the moulding plant, or got thermally modified (no more than 5%).

5.3.1.1.2 Thermal Modification Process

The first step for thermal modification was stacking the wood; they used sticks in between every layer of the material for the air to flow, once it was inside the chamber,

as shown in Figure 17. Two operators were in charge of stacking and loading the material into the chamber. These operations took, in total, approximately 1 hour. Company 1 produced batches of 3,000 board feet in each charge.



Source: Company 1

Figure 17. Finished Product

After the wood was loaded in the chamber, the process for modification began. All the schedules for each specie vary from one another. Company 1 had seven different treatments, one for each specie that they produced, depending on thickness of wood offered by the company. The schedules for each company are not mentioned in this project, for proprietary reasons. Each company provided an overall review of the process, without providing this information. For this reason, schedules have not been covered. Setting up the schedule on the computer took approximately ten minutes, and only required one operator. The machine measured pressure, wood temperature, and chamber temperature, using six temperature readings around the chamber. The first phase started by raising the heat to the first step in the schedule, and then a vacuum pump extracted all the oxygen. Oxygen extraction was necessary because the wood reached its combustion point, and if there was any oxygen in the chamber, the material would ignite. The next step was targeting an exothermic

reaction, where the wood temperature was higher than the chamber temperature, and chemical reactions took place. In the last part of the process, the chamber spent approximately 10 to 12 hours to cool the product, so the machine could be opened without the wood igniting. The material could be handled approximately 24 hours after removal from the chamber. The chamber could be monitored with a cellphone app. The treatment focused on reducing the moisture content in the product, and some liquids residuals were released during the process. Once the process was complete the liquids residuals were burned.

The total treatment time, including cooling, was 38 to 46 hours, however it varied according to the species treated. Figure 18 shows the chamber used by company 1. This chamber used a closed system, like the one described at the beginning of this chapter.



Source: Company 1

Figure 18. Chamber in Company 1

Once the product had cooled, the chamber was unloaded, and the wood was ready for regrading. At the time the data was collected, the production of TMW was run by

order, and was regularly kept in inventory, which consisted of approximately 30,000 board feet. The quality control of the output was verified by observation of the graphics displayed on the computer of the machine during the treatment and by measuring the moisture content of the material, which was 5%.

5.3.1.1.3 Associated Costs, Current Markets, and Other Aspects

The production cost associated with TMW was approximately \$500 per thousand board feet, and the cost of the equipment and installation of the machinery was approximately \$750,000. The company produced many other products, with TMW only representing approximately 1% of the total sales. Even though they had eight or more species available for thermal modification, the highest customer demand was for yellow poplar and ash, with an average order quantity of 5,000 board feet. Maintenance of the system required that every six to eight cycles, the seals of the doors needed to be replaced, and every seal had a cost of \$700.

Since the production of TMW was run by order, the company did not keep a large amount of product in inventory, compared to the rest of the wood that they manufactured. At the time of the study, they had 26 million board feet of non-thermally modified wood in stock, with a value of \$5 million, and they stated that the TMW inventory seemed insignificant compared to those values. Company 1 said that the modified product could stay in stock for years without loss of quality or getting damaged, due to its low capacity to reabsorb moisture.

5.3.1.1.4 Value Stream Map

Table 40 shows the numeric values provided by the company for the construction of the value stream map.

Table 40. VSM Company 1 needed information

	Min	Max	Average	Units
Chamber batch			3,000	BF
Usage	2	3	2.5	Times/week
Monthly demand	24,000	36,000	30,000	BF
Computer set up			10	Minutes
Stacking and loading			1	hour
Treatment time	38	46	42	hour
Inventory level			30,000	BF

Since the company produced TMW only by order, it was possible to calculate the monthly demand according to how often they made use of the chamber. The personnel in charge explained that the machine was used two to three times a week, with an average batch of 3,000 BF; this means that they had a monthly demand for 30,000 BF.

With the information in Table 33, it was possible to identify the values related to each activity in the manufacture of TMW for company 1. The first process identified was the stacking of the material, which had a cycle time of one hour per 3,000 BF charge. The activity of stacking required two operators, who were employed eight hours per day, but only used one hour (0.125 days) to stack the material. Considering that the company used the chamber two to three times per week, the stacking operation required, on average, 2.5 hours per week and ten hours per month (Table 41).

Table 41. Stacking process information company 1

Stacking		
Cycle time (CT)	1	h/charge
	0.13	days/charge
	2.5	h/week
	10	h/month
Availability	8	h/day
Working days	10	days/month
Workforce	2	operators

The activity of thermal modification started with the setup of the computer, which required one operator who had an availability of 24 hours per day. This operator worked eight hours a day but if something happened to the chamber, the operator received a notification with a cellphone application. The set up took ten minutes (0.0069 days) per charge. Once the computer had been configured with the correct schedule, the wood spent, on average, 42 hours (1.75 days) per charge, meaning that the machine also had to be available 24 hours a day. The operator had a display of the computer's screen on his phone, with graphics and alerts. In case of an emergency, the operator had to be available to take care of the situation. According to the machine's usage, wood modification required 17.5 days per month. The values mentioned before are shown in Table 42.

Table 42. Treatment process information company 1

Treatment		
Cycle time (CT)	42	h/charge
	1.75	days/charge
	105	h/week
	420	h/month
Availability	24	h/day
Working days	17.5	days/month
Set up (ST)	10	min/charge
	0.17	h/charge
	0.01	days/charge
Workforce	1	operator

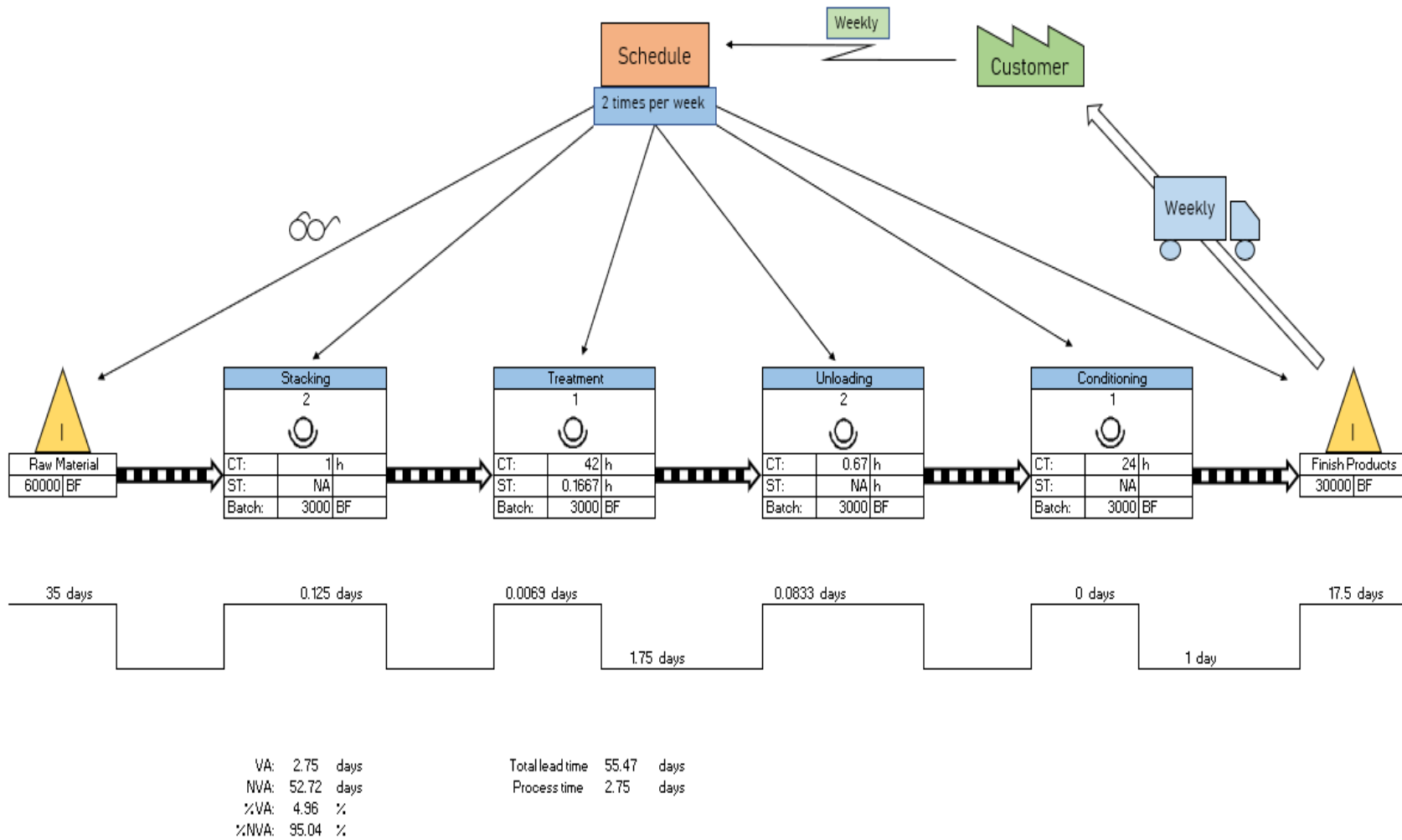
Once the cycle was finished, the chamber needed to be unloaded. This activity required two operators, who also had an availability of eight hours per day and it took approximately 40 minutes (0.083 days) per charge. The necessary data for the unloading operation is shown in Table 43. After the wood was unloaded, they let the product condition for around 24 hours before it continued its path.

Table 43. Unloading process information company 1

Unload		
Total time	40	min/charge
	0.67	h/charge
	0.08	days/charge
	2.5	h/week
	10	h/month
Availability	8	h/day
Working days	10	days/month
Workforce	2	operators

The inventory level of the finished product was 30,000 BF, which represented 17.5 days, and the raw material inventory level was 60,000 BF, which represented 35 days; this was according to the machine's working hours, and its availability of 24 hours per day.

With the calculations made, the VSM for company 1 is shown in Figure 19.



Source: Elaborated

Figure 19. VSM Company 1

The total value-added time (VA) corresponded only to the part of the process where the wood was being treated, the rest of the operations qualified as non-value-added activities. The total lead time calculated was 55.47 days, and the total process time only took 1.75 days. The VA activities represented 3% of the total lead time, while NVA activities corresponded to 97% of the total lead time.

5.3.1.1.5 Production and Inventory Costs

Company 1’s production costs were \$500 per thousand BF. Producing each batch had a cost of \$1,500. Considering an average selling price of \$4 for their products, the total inventory value for their finished goods was \$120,000. According to the Hardwood Market Report, for October 2019, the prices for FAS kiln-dried wood per BF are shown in Table 44. These were the species and thickness that company 1 offered.

Table 44 FAS kiln-dried wood prices for company 1

Species and Thickness	Kiln Dried
4/4 Ash	\$1.400
6/4 Ash	\$1.665
8/4 Ash	\$1.790
4/4 Poplar	\$1.165
5/4 Poplar	\$1.230
8/4 Poplar	\$1.275
Average	\$1.421

Source: Hardwood Market Report

The total inventory value dedicated to TMW was \$85,250, according to the prices of the products mentioned in Table 32.

5.3.1.1 Company 2

All the information was gathered during a guided visit to the mill with the head of facilities. An interview was a crucial element to collect data, but the research team also used observation for understanding the process flow.

5.3.1.1.1 Prior to the Thermally Modified Wood Process

The raw material came from sawmills, and it was necessary to dry the material. First, the lumber was stacked and placed in the air-drying yards for some time. Times varied depending on the species. After the air-drying time, the material was introduced into a dry kiln, to obtain a 6% to 8% moisture content. The product spent seven to ten days in the kiln. Then they let the wood condition or cool down, followed by grading the material, and lastly sorting depending on the width, trying to pull 6.5 to 7.5 inches of width. This product continued its regular processing at the mill or got thermally modified.

5.3.1.1.2 Thermal Modification Process

Once the wood had the correct moisture content, it needed to be stacked again with another type of stick. This was necessary to allow the air to flow easily through the wood, while in the chamber. Two workers were necessary for stacking, which took approximately 40 minutes, and the usual charge was 3,000 board feet. When they finished stacking, they loaded the wood into the chamber. After they closed the chamber's door, another operator set up the computer with the appropriate schedule. This operation took approximately two minutes. The time that the material spent in the kiln depended on the species and thickness being treated but, according to the personnel, it spent two to three days inside the chamber. The schedule for thermally modifying the wood took a significant amount of time getting to the desired temperature and approximately nine to ten hours for cooling, following treatment, so it would be safe to open the chamber door. This chamber used an open system to modify the material. When the product had finished, they unloaded it. This took approximately 40 minutes and the material then sat for ten days for conditioning. After conditioning, it was sold or continued to moulding related activities.

The quality control of the finished products depended on aspects such as visible defects present in the wood and correct moisture content, which was reduced to a range of 0% to 2%. Primarily the target was to obtain a specific color that was part of the customers' requirement. Even though the company's TMW production was

run to order, they kept an inventory of approximately 100,000 board feet at their facilities. Figure 20 shows a part of the stock that company 2 kept.



Source: Company 2

Figure 20. Company 2 inventory

5.3.1.1.3 Associated Costs, Current Markets, and Other Aspects

Thermally modified production at company 2 was divided into two main costs: electricity for running the chamber, for which they paid around \$250 per charge, and the disposal of the residues. When the material was inside the chamber being treated, it released liquids and acids, because of the goal to reduce moisture content, but these residues needed to be disposed of correctly. The company paid \$250 every three weeks for the disposal of 250 gallons of the wood's remnants. They stated that the total cost of manufacturing one batch on TMW was approximately \$500. The maintenance of the chamber was done every three to four charges; it took 2 hours to clean and, once every month, it was necessary to perform a deep clean.

The company's sales were in national and international markets. They stated that the non-thermally modified wood production per year was nine to ten million board feet, 70% of which was exported.

For TMW, company 2 had strong demand from the building industry. They explained that there existed a target market that searched for eco-friendly, green, no chemical, plastic-free products, and TMW qualified perfectly. Their star product was thermally modified poplar for siding. It is essential to mention that most of the treated wood that the organization offered had already gone through the moulding process, and could be used as a finished good right away.

5.3.1.1.4 Value Stream Map

During the visit to company 2, the author was able to collect the information shown in Table 45, which was necessary for the value stream map construction. The treatment time is the average between the maximum (3 days) and minimum (2 days) treatment time.

Table 45. VSM Company 2 needed information

	Average	Units
Chamber batch	3,000	BF
Usage	2.74	Times/ week
Monthly demand	30,000	BF
Computer set up	2	Minutes
Stacking and loading	40	Minutes
Unloading	40	Minutes
Conditioning	10	Days
Treatment time	2.5	Days
Inventory level	100,000	BF

Company 2 only manufactured TMW by order, with a monthly demand of 30,000 BF. Since the processing of the wood took two to three days per charge, and the

chamber ran at any possible time, this meant that the company could use the machine 2.74 times per week, which was calculated using the treatment time plus the stacking, loading, unloading, and setup times. The chamber ran with an average batch of 3,000 BF per charge.

The first operation was the raw material stacking. This operation took 40 minutes per charge and required two operators with an available time of 7.5 hours a day, but they were only needed for 0.67 hours (0.089 days). Considering that the usage of the machine was two times per week, the stacking operation required 1.33 hours per week and 5.33 hours per month. The calculation of the stacking process was the same as the unloading process, since all the variables included were equal. Table 46. shows the numeric values for each operation.

Table 46. Stacking and unloading process information company 2

Stacking and Unload		
Total time	40	min/charge
	0.67	h/charge
	0.09	days/charge
	1.33	h/week
	5.33	h/month
Availability	7.5	h/day
Working days	8	days/month
Workforce	2	operators

The next activity was wood modification. First, an operator, who had an availability of 24 hours a day, set up the computer, which only took 0.033 hours (0.0014 days). After the computer had been configured, the material spent, on average, 2.5 days inside the chamber. Both the machine and the operator had an availability of 24 hours since it was a continuous process, and in case of an emergency, the operator would receive a notification on his phone and had to respond. The mentioned values are shown in Table 47.

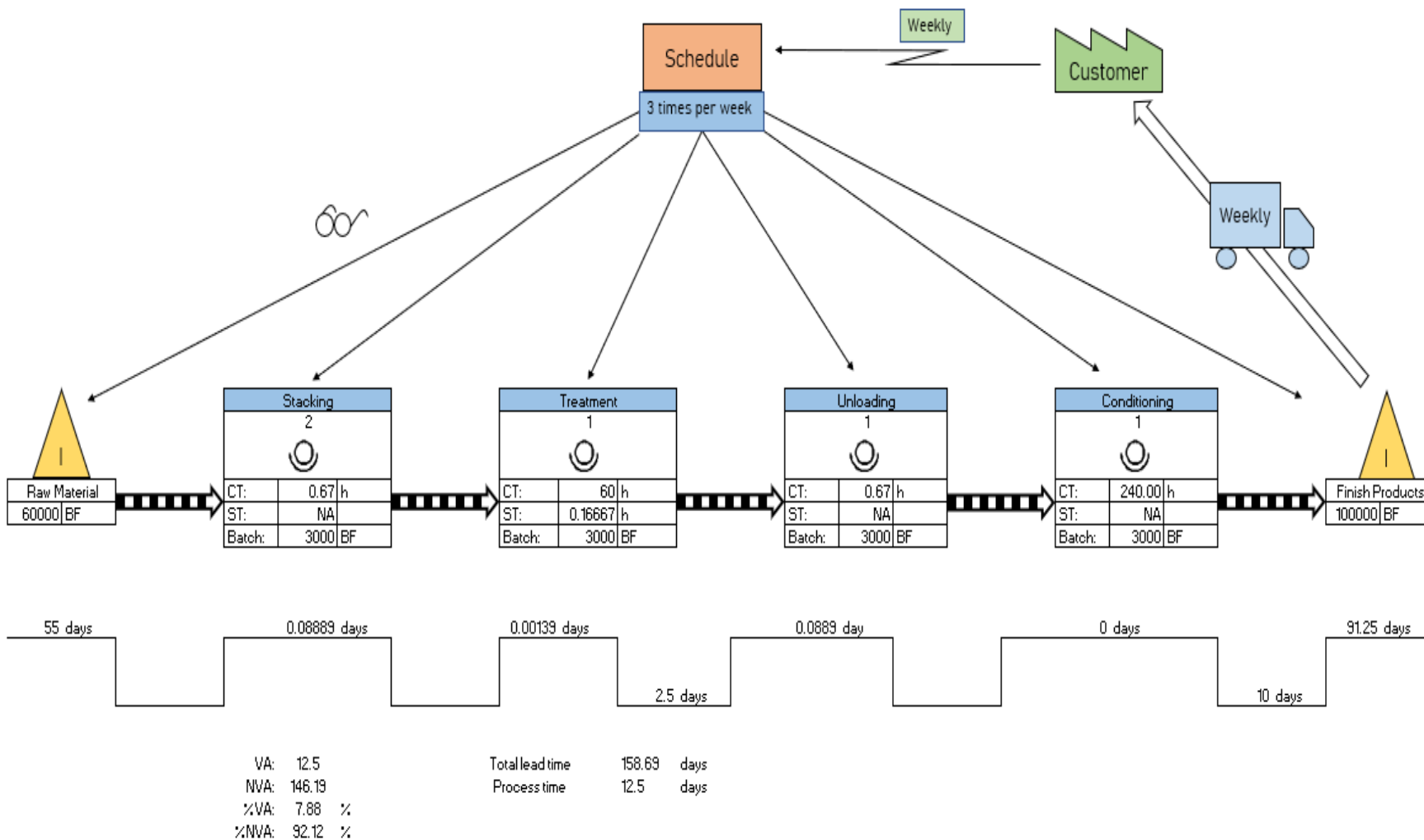
Table 47. Treatment process information company 2

Treatment		
Total time	60	h/charge
	2.5	days/charge
	120	h/week
	480	h/month
Availability	24	h/day
Working days	20	days/month
Set up	2	min/charge
	0.03	h/charge
	0.00	days/charge
Workforce	1	operator

The two last steps were unloading the product and letting it sit for conditioning. The unloading calculation was equal to the stacking process. The conditioning of the wood took ten days before it could be handled.

Company 2 had an inventory of 100,000 BF of TMW, which represented 66.67 days, and a raw material inventory level of 60,000 BF, which represented 55 days, considering the machine availability of 24 hours.

With all the calculations made, it was possible to elaborate on a VSM for company 2, and it is shown in Figure 21.



Source: Elaborated

Figure 21. VSM company 2

The total value-added time (VA) corresponded only to the part of the process where the wood was being treated, the rest of the operations were qualified as non-value-added activities. The total lead time calculated was 158.69 days, and the total process time only took 2.5 days. The VA activities represented 2% of the total lead time, while NVA activities corresponded to 98% of the total lead time.

5.3.1.1.5 Production and Inventory Costs

Company 2’s production costs were \$500 per 3,000 BF (one batch). The finished goods inventory represented a cost of \$16,667. However, the TMW BF had an average price of \$3.95. This means that the total value of the finished goods inventory was approximately \$395,000.

To estimate the value of the raw material, prices for kiln-dried wood for FAS grade per BF from the October 2019, Hardwood Market Report, (Table 48) were used.

Table 48. FAS grade kiln-dried wood prices for company 2

Thickness and Specie	Price
4/4 Ash	\$1.400
5/4 Ash	\$1.515
6/4 Ash	\$1.665
8/4 Ash	\$1.790
5/4 Soft Maple	\$1.790
4/4 Poplar	\$1.165
5/4 Poplar	\$1.230
6/4 Poplar	\$1.250
8/4 Poplar	\$1.275
Average	\$1.453

Source: Hardwood Market Report

According to the average price of the products mentioned in Table 41, the raw material inventory level represented \$87,200. Since the company produced its raw material, the cost per thousand board feet was from \$150 to \$200. This means that their amount of raw material had a total production cost of \$10,500.

5.3.1.2 Company 3

All the information was gathered through a guided visit to the mill with the head of the TMW sales department and the production manager. An interview was a crucial element to collect data, but the research team also used observation for understanding the process flow.

5.3.1.2.1 Thermal modification process

Company 3 made use of two thermal modification chambers; one used an open system and the other a closed system. Initially, for each chamber, it was necessary to stack the wood with special sticks and introduce it into the machine; this operation took between 3 to 3.5 hours for 3,200 BF. Once the wood was inside the chamber, they set up the computer with the needed schedule, and this operation took around two minutes. The heating process time of the material varied according to each machine. Once the processing cycle was finished, the product was taken out of the chamber and off the sticks. This operation was relatively fast and took around 30 minutes. Table 49 displays the differences between each machine considering average batch, treatment time, the number of schedules, and final moisture content (MC) of the product.

Table 49. Differences between closed and open system chambers

	Closed system	Open system
Average Batch	2,800 BF	3,000 BF
Heat treatment time	25 hours	36 hours
Number of schedules	20	20
Final MC	2.50	5.75

It is important to mention that the final product was not sold to the client according to the machine on which it was processed. The variation of products and schedules was determined by the species and dimensions the company offered.

The annual demand for TMW was around 400,000 BF, and after years of studying the market and sales regarding this product, they established an initial inventory of

100,000 BF and finished product inventory of 100,000 BF. Even though TMW manufacturing was run by order, company 3 had a constant queue of clients ordering the product.

5.3.1.2.2 Associated Costs, Current Markets, and Other Aspects

During the process of thermal modification, the wood released a highly acidic liquid. These residues had to be properly disposed of by an external party. A 4800-gallon tank collected the waste from both machines and was emptied once a month. Regarding the electricity needed to run the chambers, company 3 used solar panels that provided the energy to keep the machines working. This last aspect allowed the company to advertise an already green product with an ecofriendly manufacturing process.

5.3.1.2.3 Value Stream Map

As mentioned before, the company used two different machines with distinctive characteristics. For the construction of the VSM, the production capacity of the plant was calculated as the sum of what both machines could produce, and the weighted average of the times involved. Tables 50 and 51 show the related values for each machine.

Table 50. Closed system chamber at company 3

Closed System		
Chamber capacity	3,200	BF
Usage	5.8	Times/week
Computer set up	2	Minutes
Stacking and loading	3.25	Hours
Unloading	30	Minutes
Treatment time	25	Hours

Table 51. Open system chamber at company 3

Open System		
Chamber capacity	3,000	BF
Usage	4.24	Times/week
Computer set up	2	Minutes
Stacking and loading	3	Hours
Unloading	30	Minutes
Treatment time	36	Hours

With the times and batch size of each machine, it was possible to calculate the total production capacity of the plant. The batch size corresponded to the sum of both chambers' capacities. As for the times, it was necessary to calculate a weighted average. First, a certain weight was assigned to each machine. This weight was the result of dividing the batch size of each machine by the sum of both batches, as shown in the following section.

Closed system chamber:

$$\frac{3200}{6200} = 0.51$$

Equation 9. Production Capacity for Closed System Chamber.

Open system chamber:

$$\frac{3000}{6200} = 0.48$$

Equation 10. Production Capacity for Open System Chamber.

The involved activities weighted average was calculated with the obtained values; this was done by multiplying each percentage with its respective process time and adding the results. There were three identified activities in the manufacturing process: stacking, set up and treatment, and unloading. The following section shows the calculation of the cycle time of each activity by adding together both machines.

Stacking time:

$$0.52 * 3.25 = 1.68$$

$$0.48 * 3.05 = 1.47$$

$$Total = 3.15 \text{ hours}$$

Equation 11. Stacking time estimation.

Computer set up time:

$$0.52 * 2 = 1.03$$

$$0.48 * 2 = 0.97$$

$$Total = 2 \text{ minutes}$$

Equation 12. Computer set up time estimation.

Treatment time:

$$0.52 * 25 = 12.90$$

$$0.48 * 36 = 17.42$$

$$Total = 30.32 \text{ hours}$$

Equation 13. Treatment Time.

Unloading time:

$$0.52 * 30 = 15.48$$

$$0.48 * 36 = 14.52$$

$$Total = 30 \text{ minutes}$$

Equation 14. Unloading time estimation.

These results were utilized in the construction of the VSM. Table 52 shows the results of the combination of the two chambers times and batches.

Table 52. VSM Company 3 needed information

Chamber capacity	6200	BF
Usage	4.9	Times/week
Monthly demand	33,333	BF
Computer set up	2	Minutes
Stacking and loading	3.15	Hours
Unloading	30	Minutes
Treatment time	30.32	Hours
Inventory level	100,000	BF

Both machines provided a total capacity of 6,200 BF of TMW. Considering the treatment, set up, stacking, and loading and unloading, times were calculated with a weighted average for both machines. The total usage of the chambers was 4.9 times per week. This result was obtained by adding all the involved times and dividing them by seven days, to see how many times a week the machine could run. Both machines had an availability of 24 hours, 7 days a week. This was because it was a process running continuously for more than a day. However, the availability for stacking the wood was eight hours per day from Monday to Friday.

Both machines required the same activities to modify the product. The first identified activity was stacking and loading the wood; this took 3.15 hours (0.394 days) for a batch of 6200 BF. This operation needed two workers, and since the machine was used 4.9 times per week, the operators spent 15.57 hours per week and 62.28 hours per month performing this activity. Table 53 displays this information.

Table 53. Stacking process information company 3

Stacking and Load		
Total time	3.15	h/charge
	0.39	days/charge
	15.57	h/week
	62.28	h/month
Availability	8	h/day
Working days	19.76	days/month
Workforce	2	operators

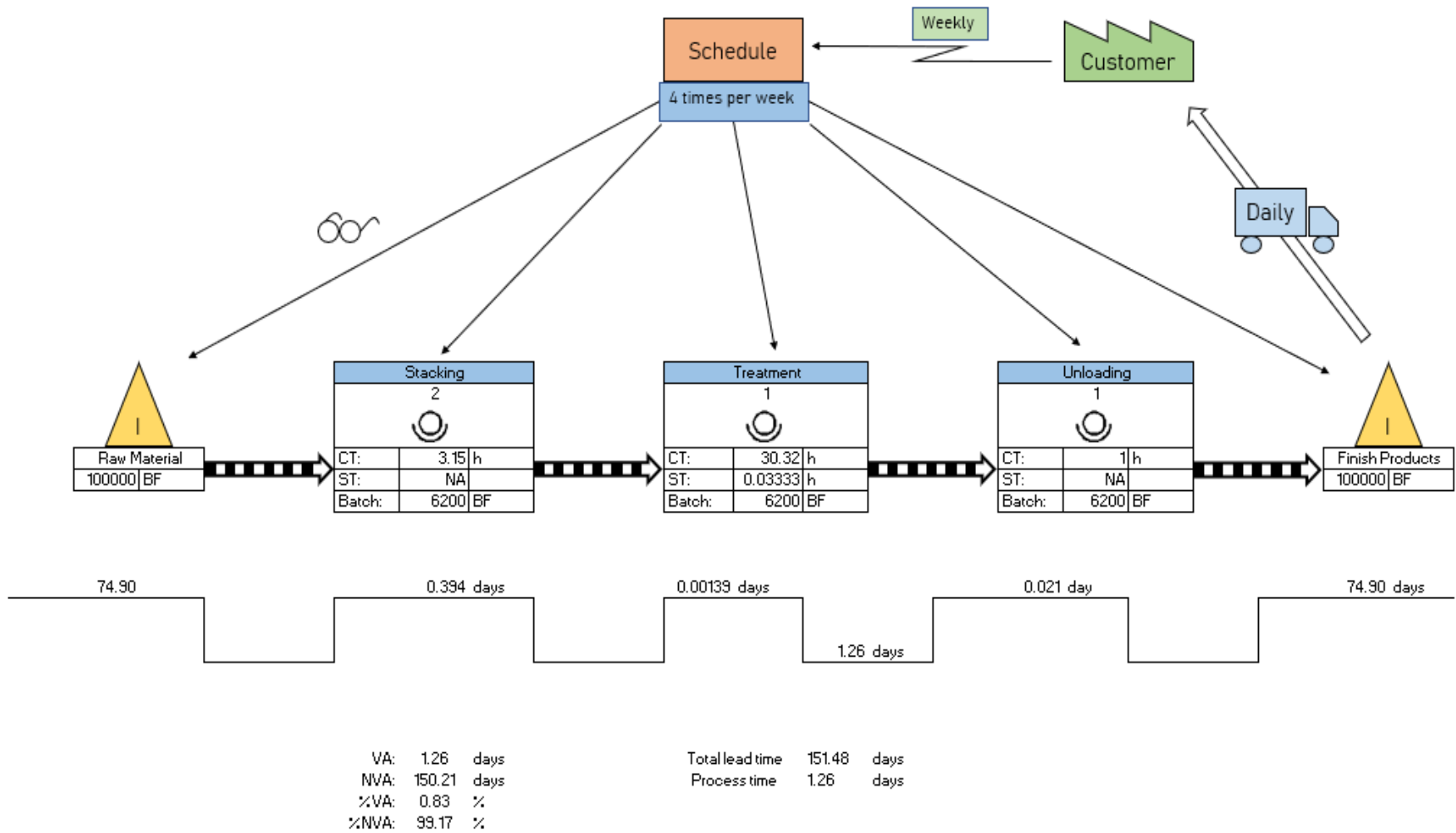
The following process was the modification of the material. First, one of the two available operators configured the computer with the required schedule. The configuration took two minutes (0.03 days). Once the chamber was configured, and the door closed, the heat treatment began; this activity had an average duration of 30.32 hours (1.26 days) per charge. The machine and the operator had an availability of 24 hours. The times related to the wood heat treatment are shown in Table 54.

Table 54. Treatment process information company 3

Processing (VA)		
Total time	30.32	h/charge
	1.26	days/charge
	149.80	h/week
	599.18	h/month
Availability	24	h/day
Working days	24.97	days/month
Set up	2	min/charge
	0.03	h/charge
	0.00	days/charge
Workforce	1	operator

Lastly, once the wood had finished its modification cycle, only the unloading of the product was left. This operation required two operators and took approximately 30 minutes (0.021 days) per charge. The wood did not need any conditioning once it was taken out from the chamber. In fact, it could be shipped right away.

The company kept a raw material and finished product inventory of 100,000 BF each; this represented 74.9 days of inventory. All these calculations allowed the construction of the VSM for company 3, which is shown in Figure 22.



Source: Elaborated

Figure 22. VSM company 3

The total VA time corresponded only to the part of the process where the wood was being treated. The rest of the operations qualified as NVA activities. The total lead time calculated was 151.48 days, and the total process time only took 1.26 days. The VA activities represented 1% of the total lead time, while NVA activities corresponded to 99% of the total lead time.

5.3.1.2.4 Production and Inventory Costs

Company 3 did not specify their production costs but considering an average selling price of \$3 for the products they offered, the current final product inventory had a value of \$300,000, as shown in Equation 14. Table 55 shows the prices for November 25th of 2019. Regarding the raw material inventory, the average price for the products company 3 offered was \$1.39. This means the value of the raw material was \$138,833.

Table 55. TM Wood Prices for Company 3

Thickness and Specie	Price
4/4 TM Ash	\$3.24
4/4 TM Soft Maple	\$3.35
4/4 TM Poplar	\$2.40
Average	\$2.99

$$Inventory\ Value = Inventory\ Level * Selling\ Price$$

$$100,000 * 2.99 = 299,667$$

Equation 14. Final Product Inventory Value.

5.3.2 Value-Added and Non-Value-Added Activities Analysis

This section discusses the analysis for activities adding value to the process through the utilization of Yamazumi charts; these charts are a visual tool that displays the work elements within a process. Yamazumi charts include only the activities of the process and do not show the inventory days. It is a visual representation of the balance of cycle time with the valued added activities versus the non-value activities

represented in days. Figures 23, 24, and 25 compare the VA and NVA activities at each company.

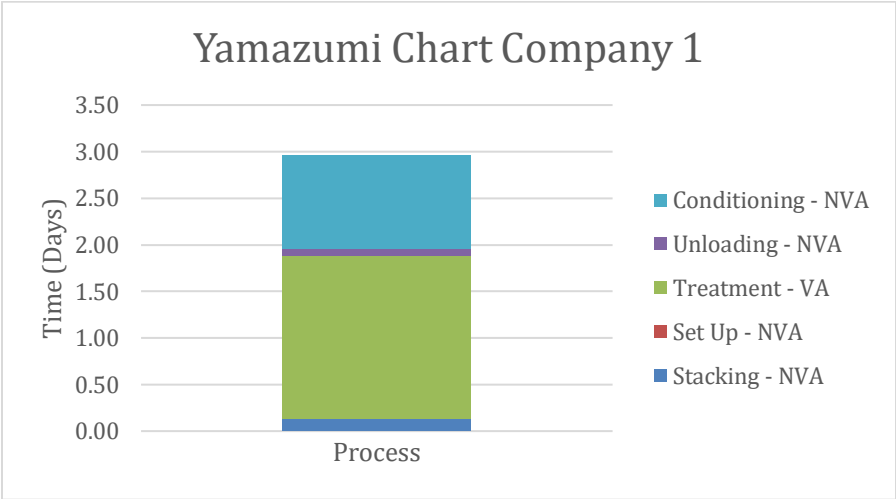


Figure 23. Yamazumi Chart Company 1

Figure 23 shows that company 1 only had one activity adding value to the process; the other three activities were considered non-value adding. As observed, the widest section was associated with the treatment, which was the only value-adding activity.

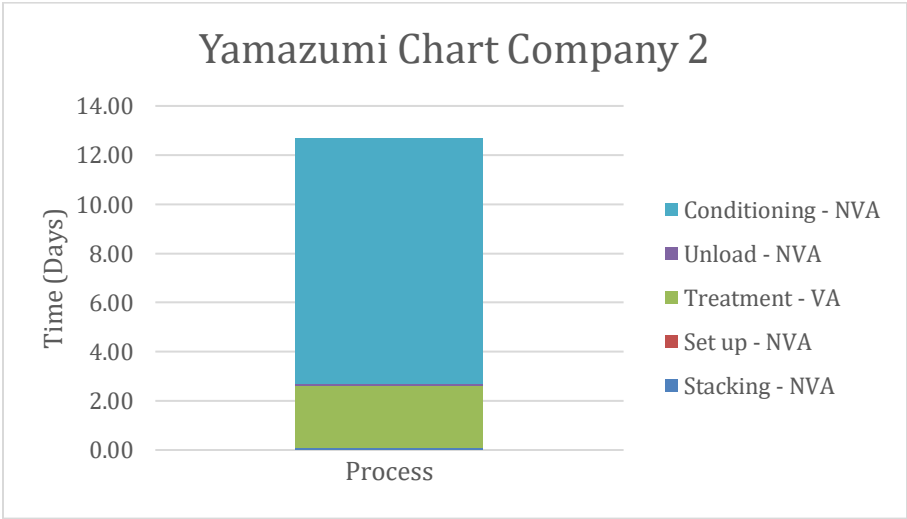


Figure 24. Yamazumi Chart Company 2

Figure 24 shows that company 2 only added value to the process with the treatment activity, while most of the time was spent on the conditioning activity. Stacking and unloading were almost imperceptible due to their short cycle time.

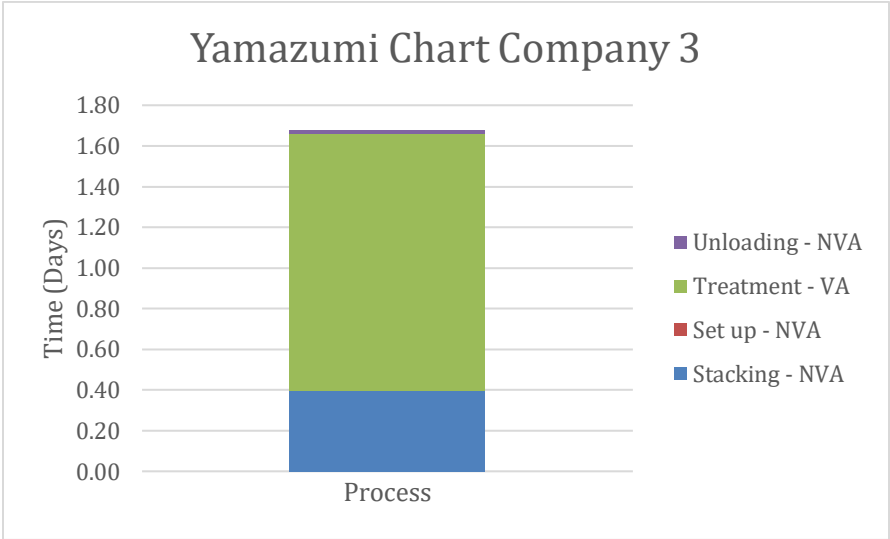


Figure 25. Yamazumi Chart Company 3

Figure 25 shows that company 3 only had the treatment of the wood as a value-adding activity while computer set up, stacking, and unloading qualify as non-value adding. In fact, the setup and unloading activities were almost null compared to the other activities, due to their short cycle time.

5.3.3 Comparison Between Companies and Problem Identification

Companies 1, 2, and 3 shared specific characteristics, but their final lead times, VA, and NVA percentages varied. Table 56 shows the essential aspects of the three companies.

Table 56. Value comparison between companies

	Company 1	Company 2	Company 3
Average batch	3,000 BF	3,000 BF	6,200 BF
Raw Materials Inventory	60,000 BF	60,000 BF	100,000 BF
Raw Material Inventory Value	\$85,250	\$87,200	\$138,833
Final Product Inventory	30,000 BF	100,000 BF	100,000 BF
Finished Goods Inventory Value	\$120,000	\$395,000	\$299,667
Monthly demand	30,000 BF	30,000 BF	33,333 BF
Lead time	55.47 days	158.69 days	151.48 days
VA	3%	2%	1%
NVA	97%	98%	99%
Takt time	1.75 days per batch	2.74 days per batch	4.64 days per batch
Production Costs	\$1,500 per batch	\$500 per batch	Not specified

The three companies studied had high NVA activity percentages and hence, low VA activity percentages. However, the best metrics belong to company 1. They had the lowest lead time and the highest VA percentage. What differentiated company 1 from the other two companies was their final product inventory. Each of the VSM showed that increments in lead times were mainly related to the inventory levels at the beginning and the end of the process. Since company 1 had the lowest inventory levels, its lead time was reduced. This created concern regarding how much inventory should be kept. A series of elements were related to this such as demand, storage costs, and product lifespan.

Another factor that could influence the long lead times was observed in company 2 when they included a ten-day conditioning time for the product. This conditioning

time was not observed at the other two companies. Company 1 only conditioned the product for 24 hours, but they explained that the purpose was for the wood to reach a cool enough temperature for the operators to handle it. Company 3 said that the wood could be handled as soon it came out of the chamber.

Moreover, company 3 had the longest stacking time (3.15 hours). They explained that this happened because the wood boards that make up the batches needed to be aligned correctly before introducing them in the chamber. Nevertheless, the other two companies required 2.15 hours less stacking and they also required good board alignment. Stacking lumber was done manually by two operators, which could have been the reason for the delay. As for the unloading time, it also affected the lead times; however, none of the companies referred to it as a critical part of the process.

Two other factors that could have affected the VA percentage were cooling times inside the chamber and the disposal of the liquid residues. Companies 1 and 2 mentioned that the machines took too many hours cooling the material, and they hoped to find a way to reduce this time without affecting the product's properties. The cooling was an action of the chamber using air added by the chamber. Company 3 did not specify any concerns on the cooling of the material for their process. Each company handled the acidic liquids generated by the process differently. Company 1 burned these residues, with complement equipment the chamber had; therefore, they did not incur disposal expenses. Company 2 collected the material using external equipment provided by the chamber, and paid a third-party company to dispose the material. Company 3 used to burn the residues, but this brought problems with the machines that affected their process, and they ended up spending more on maintenance costs. The machine's frequency of use may have been related to the damages that burning residues caused.

According to inventory levels, the three companies tried to offer clients short shipping periods. They managed to do this by keeping a final inventory level that gave them the flexibility to assemble an order in less time. Companies 1 and 2 clearly stated

that they produced TMW by order, and once the client had placed the order, they communicated that the product would be shipped in three weeks for company 1 and six weeks for company 2. These times varied if the product needed to be moulded or not. Company 3 also stated that they ran by order; however, they indicated they had a regular queue of clients needing the product and they offered clients two weeks for sending the product. Some inconsistencies came to light when these inventory levels were analyzed. First, the three companies shared a remarkably similar demand, which was 30,000 BF per month, but two of them kept 100,000 BF in their finished product inventory. TMW can spend more than a year in a warehouse without damage, due to the modification it has gone through. Nevertheless, maintaining that much inventory means companies incur unnecessary expenses.

The three companies used similar batches sizes in their machines, to try to take advantage of the chamber's maximum capacity in each charge. In that way, they could obtain more product in less time. The batch sizes could be reduced; however, because the machinery would require a similar amount of electricity, and the process takes many hours; it was more beneficial to fill the chamber.

Heads of the companies stated that they believed they achieved the right schedules, right inventory levels, and right process, in general, through trial and error. When doubts regarding the kiln schedules appeared, they contacted the chamber's manufacturer for answers. Each of the companies assumed that they were developing the right process, since the benchmarking of this product was limited. None of the companies were fully dedicated to TMW production; it was just another product that they offered.

The following root-cause diagram in Figure 26 displays the reasons mentioned for high percentages of non-value-added activities.

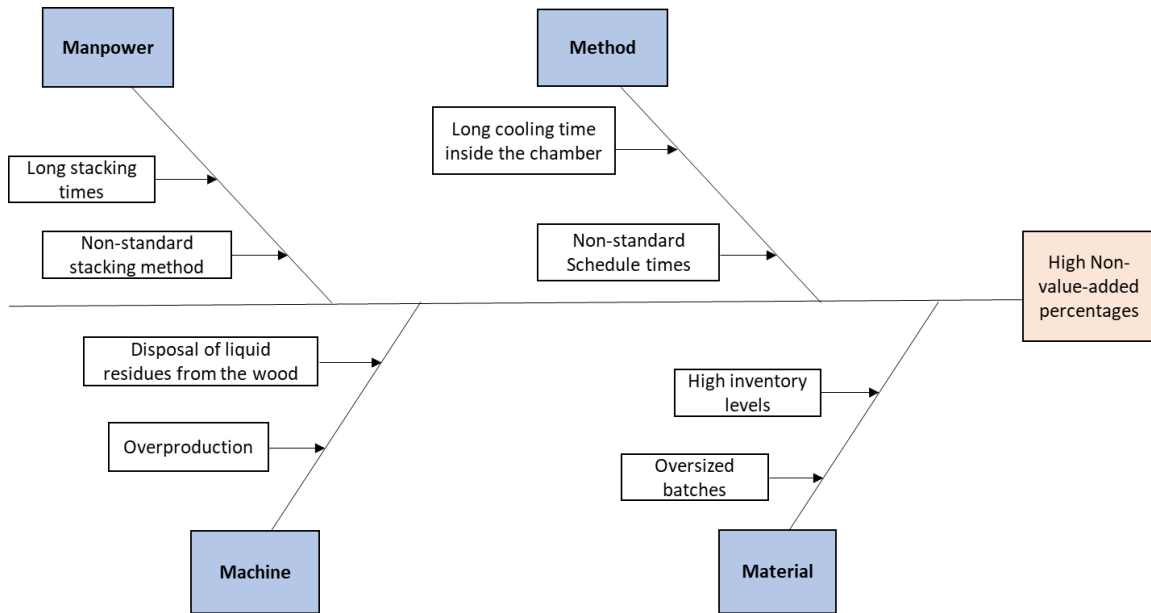


Figure 26. Root - Cause diagram of the current TM wood production process

In addition to a root-cause diagram, a 5-why's analysis was also developed. The initial problem considered was the high percentage of non-value-added activities that the three companies shared. Table 57 shows the analysis used to identify the root cause of each problem mentioned in the root-cause diagram.

Table 57. 5-Whys Analysis

Problem: High Non-value-added percentages.			
Workforce	Method	Machine	Material
<p>1. Why? High stacking times.</p> <p>2. Why? Two operators ensemble the batches manually.</p> <p>3. Why? The batches must be stacked symmetrically.</p> <p>4. Why? The chamber size requires a standard batch size.</p> <p>5. Why? The air must flow evenly inside the chamber for cooking.</p>	<p>1. Why? Company 3 not having conditioning times.</p> <p>2. Why? It is stated as part of the schedule or for cooling the wood.</p> <p>3. Why? After the chamber cycle time, wood is still not ready to be handled.</p> <p>4. Why? The schedule is not appropriated.</p> <p>5. Why? The unfamiliarity of improved schedules.</p>	<p>1. Why? Disposal of liquid residues.</p> <p>2. Why? The wood releases acidic liquids.</p> <p>3. Why? The heat treatment removes moisture from the wood.</p> <p>4. Why? It is part of the product specifications.</p> <p>5. Why? It benefits the material.</p>	<p>1. Why? High inventory levels.</p> <p>2. Why? The company estimates large quantities as correct inventory levels.</p> <p>3. Why? It gives the flexibility to dispatch the product more often.</p> <p>4. Why? They offer short shipping periods to their clients.</p> <p>5. They sell the product to a specific market that values prompt deliveries.</p>
	<p>1. Why? Long cooling times inside the chamber</p> <p>2. Why? The schedule spent many hours cooling the wood.</p> <p>3. Why? Is a security measure for opening the chamber without the product catching on fire?</p> <p>4. Why? The wood reaches temperatures above its burning point.</p> <p>5. Why? It is a schedule requirement for obtaining the correct product.</p>	<p>1. Why? Overproduction</p> <p>2. Why? The company manufactures more of what the monthly demand is.</p> <p>3. Why? They destined a certain quantity for inventory.</p> <p>4. Why? They have defined that keeping inventory is beneficial.</p> <p>5. Why? It gives them the flexibility to ship products more often.</p>	<p>1. Why? Oversized batches.</p> <p>2. Why? They exploit the chamber capacity.</p> <p>3. Why? They prefer not to waste chamber space.</p> <p>4. Why? To obtain more product in less time.</p> <p>5. Why? The process takes to many hours.</p>

Continuation Table 57

Problem: High Non-value-added percentages.			
Workforce	Method	Machine	Material
	1. Why? Non-standard cooking times. 2. Why? Every company designs its schedules. 3. Why? They aim to offer a trademark. 4. Why? The consumers look for specific characteristics in the product. 5. Why? The product is mostly used as a finished product.		

Once the root-causes were established, the problems were prioritized to select which problems were going to be handled first. For achieving those, a multi vote was developed with the participation of four project members. The identified causes in the previous section are listed in one column, and team members voted to assign importance to each cause; 1 was considered the lowest in importance increasing to number 5, which was the highest in importance — Table 58, 59, 60, and 61 display the results.

Table 58. Multi vote results for team member 1

	1	2	3	4	5
Long stacking times					x
Long cooling times inside the chamber		x			
Non-standard cooking times		x			
Disposal of liquid residues	x				
Overproduction					X
High inventory levels					x
Oversized batches			x		

Table 59. Multi vote results for team member 2

	1	2	3	4	5
Long stacking times					x
Long cooling times inside the chamber	x				
Non-standard cooking times			x		
Disposal of liquid residues					x
Overproduction					x
High inventory levels					x
Oversized batches	x				

Table 60. Multi vote results for team member 3

	1	2	3	4	5
Long stacking times			X		
Long cooling times inside the chamber			X		
Non-standard cooking times		X			
Disposal of liquid residues		X			
Overproduction				X	
High inventory levels					X
Oversized batches			x		

Table 61. Multi vote results for team member 4

	1	2	3	4	5
Long stacking times	X				
Long cooling times inside the chamber		X			
Non-standard cooking times				X	
Disposal of liquid residues		X			
Overproduction					X
High inventory levels					X
Oversized batches	X				

The following step counted the number of times each column was selected for each cause. The results are shown in Table 62.

Table 62. Vote count

	1	2	3	4	5
Long stacking times	1	0	1	0	2
Long cooling times inside the chamber	1	2	1	0	0
Non-standard cooking times	0	2	1	1	0
Disposal of liquid residues	1	2	0	0	1
Overproduction	0	0	0	1	3
High inventory levels	0	0	0	0	4
Oversized batches	2	0	2	0	0

Then, each number obtained in the previous step was multiplied by the corresponding scale number to assign a weight to the corresponding answers and then every row was added. The results are shown in Table 63.

Table 63. Weighted votes summary

	1	2	3	4	5	Total
Long stacking times	1	0	3	0	10	13
Long cooling times inside the chamber	1	4	3	0	0	8
Non-standard cooking times	0	4	3	4	0	11
Disposal of liquid residues	1	4	0	0	5	10
Overproduction	0	0	0	4	15	19
High inventory levels	0	0	0	0	20	20
Oversized batches	2	0	6	0	0	8

Finally, the prioritization for solving the causes of the main problems is shown in Table 64.

Table 64. Root causes prioritization

High inventory levels	Overproduction	Long stacking times	Non-standard cooking times	Disposal of liquid residues	Long cooling times inside the chamber	Oversized batches
1	2	3	4	5	6	7

As observed, the first problem to be solved, from the team members' perspective, was the high inventory levels at the companies. The next problem was possible overproduction. After that it was observed that the process had long stacking times. The least essential problems were the disposal of the residue released by the wood, the long cooling times inside the chamber, and the oversized batches.

By analyzing the three companies, a pattern in TMW manufacturing was observed. Each of the companies had individual characteristics; however, they had similar activities for processing the material. Some conclusions regarding TMW production are:

- Thermally modified wood manufacturing can be summarized in three main activities: stacking and loading, modifying, and unloading. In two cases, conditioning time was included as the last step.
- The lead times for companies 1,2, and 3 were respectively 55.47 days, 158.69 days, and 151.48 days.
- Production costs for companies 1 and 2 were \$500 per thousand BF and \$500 per batch, respectively.
- The VA percentages for companies 1,2, and 3 were respectively 5%, 8%, and 1%.
- The finished goods inventory level for company 1 was 30,000 BF, for company 2 it was 100,000 BF, and company 3 it was 100,000 BF, representing average costs of \$15,883 and an average value of \$306,667.

- Root cause diagrams, 5 whys, and the multi-vote tool indicated that the most critical problems affecting the companies' VA and NVA percentages were high inventory levels, overproduction.

5.3.4 Lean Process Strategy - Value Stream Map Proposal

The main concern presented regarding the thermal modification process was the high percentage of non-value-added activities; several causes were identified. The three main root-causes identified were high inventory levels, and overproduction at the companies. This section focuses on designing a new and improved process strategy for TMW manufacturing, considering solutions for the problems found in the study. The improved process is displayed in a VSM.

5.3.4.1 Future Value Stream Mapping

According to the companies under study, their machines had a capacity of 3,000 to 3,200 BF. For these design purposes, the batch was established as 3,000 BF because it was the most common batch size used.

Another common variable in the companies was the monthly demand. The most common quantity was 30,000 BF per month. This was the demand used on the future VSM.

5.3.4.1.1 Main Activities in the Thermal Modification Process

There were three main activities shared by the companies; stacking of the wood, set up of the computer and treatment, and unloading. However, their cycle times varied from one company to the other. The conditioning activity was an added value activity from company 1 and 2, but it was not an activity for company 3. This proposal can not eliminate or recommend removing an activity, especially when a company believes that this activity is adding value to the process.

The treatment cycle time variations depended on factors like the wood thickness and species that were being treated, i.e., the treatment time for ash was different from yellow poplar or red maple. Another factor was the schedule that the company established. They

knew the characteristics that their clients wanted. Therefore, the schedule depended on those desired characteristics. One of the most critical requirements was the color at the end of the process. Color directly affected the time in the schedule.

Moreover, each company had established its technique for stacking and unloading the batches, but all three companies performed these activities manually, with two operators.

Lastly, the computer set up was performed in all three companies by one operator. The duration of this operation depended on the worker's abilities with the computer and the schedule's quantity of variables that were being introduced in the system.

Ranges in the VSM represent the cycle time of these primary activities since they were not modified. Tables 65, 66, and 67 show the requirements for developing each activity.

Table 65. Stacking time future VSM

Stacking time		
CT	0.67 - 3.25	h
	0.08 - 0.41	days
Availability	8	h
Workforce	2	operators

The process began with kiln-dried wood, ready for stacking. The stacking process required two operators and took between 0.67 and 3.25 hours to introduce a stack of 3,000 BF into the chamber. The employees that stacked the batches had regular availability of eight hours per day, five days per week.

Table 66. Wood treatment time future VSM

Treatment time		
CT	20 - 72	h
	0.83 - 3	days
Availability	24	h
Setup time	2 - 10	min
	0.08 - 0.42	days
Availability	24	h
Workforce	1	operator

Once the wood was inside the chamber, one operator set the computer with the required schedule; this activity took between two and ten minutes. After the computer set up, the wood spent from 20 to 72 hours being modified (0.83 to 3 days inside the chamber). The machine had an availability of 24 hours a day, and the operator was available phone in case any emergency occurs. The type of chamber is not specified since the ranges include times for both closed and open systems.

Table 67. Unload time future VSM

Unload time		
CT	0.5 -0.67	h
	0.06 - 0.08	days
Availability	8	h
Workforce	2	operators

Lastly, when the heat treatment period has concluded, two operators will take out the batches from the chamber; this operation took between 0.5 and 0.67 hours. The operator had an availability of eight hours per day for completing this activity.

According to the previous ranges, the machine could run 23 days per month, considering the total time of the process. This allowed the production of 1340 BF per day.

Two of the companies shared the conditioning activity after the wood had been unloaded from the chamber. Company 1 spent a day and company 2 spent 10 days on conditioning the product and stated that it was a necessary part of the process, so the wood can catch some moisture, since these companies had obtained a better product performance with this activity. Company 3 did not add a conditioning period and stated that once the wood was unloaded, it could be handled without a problem. Defining if this was a necessary activity or not requires an in-depth study on how the schedules affect the wood. For this design, the conditioning time considered a value-added activity and it was considered on the future VSM.

5.3.4.1.2 Inventory Levels

The inventory levels at the companies added many days to the lead times; hence, it increases the NVA percentages. For the future VSM, it was necessary to calculate the correct quantity of raw material and finished goods inventory to reduce the NVA percentages. Quesada (2010) explained how the wood industry was a victim of accumulation of inventory, and Lean thinking plays a crucial role in solving this problem, since its philosophy encourages the elimination or minimization of waste. Through the utilization of the economic order quantity (EOQ) model, it was possible to establish a relationship between the cost and how much to order or produce and the model assumes constant customer demand. The Equation 15 determines the EOQ model with two holding costs for the raw materials inventory and Equation 16 for finished goods inventory.

$$Q = \sqrt{\frac{DC_s^2}{C_h}}$$
$$\sqrt{\frac{373,333 * 450 * 2}{1.5}} = 14,967$$
$$\sqrt{\frac{373,333 * 450 * 2}{2.5}} = 11,593$$

Equation 15. EOQ estimation for Raw Material Inventory.

$$Q = \sqrt{\frac{DC_s^2}{C_h}}$$
$$\sqrt{\frac{373,333 * 1000 * 2}{1.5}} = 22,311$$
$$\sqrt{\frac{373,333 * 1000 * 2}{2.5}} = 17,282$$

Equation 16. EOQ estimation for Finished Goods Inventory.

where

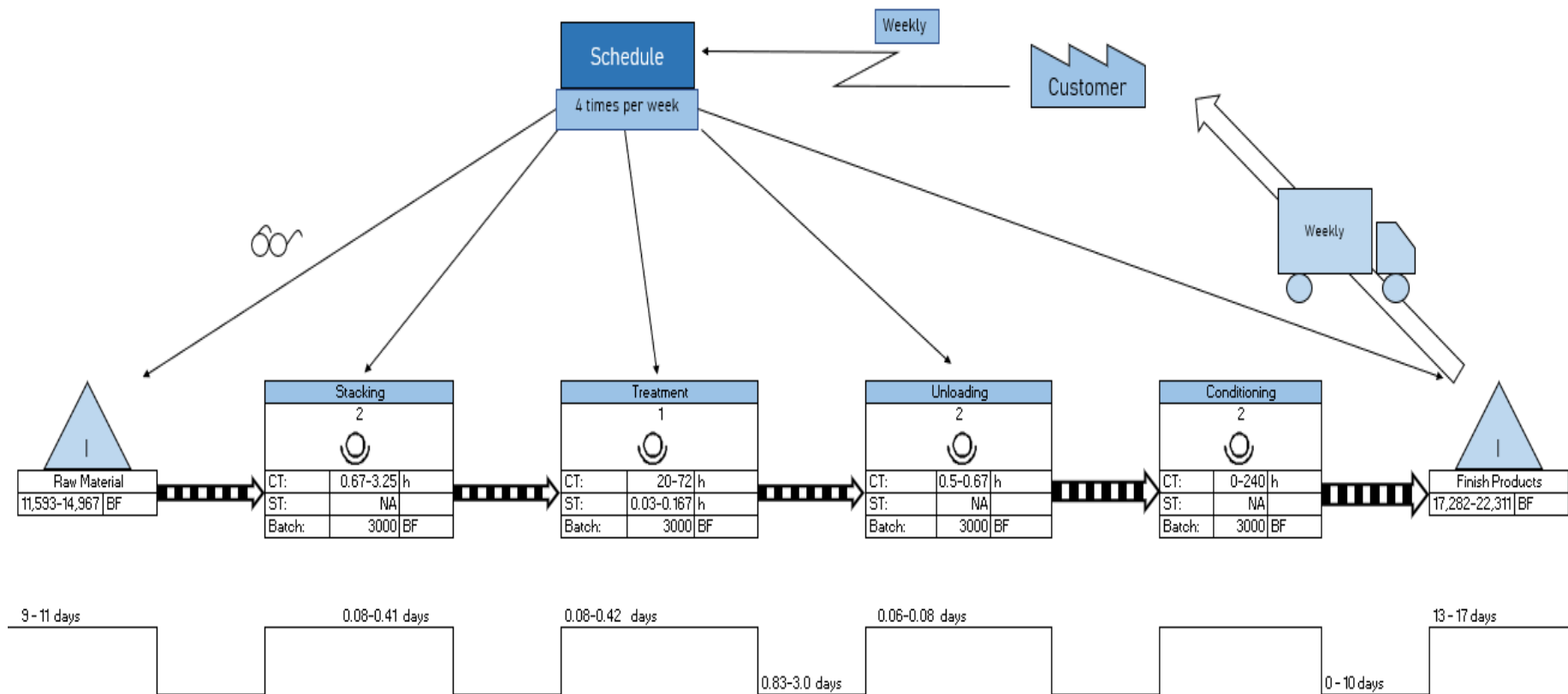
D = demand usually expressed as yearly demand,

Q = the number of units ordered per order,

C_s = the cost of setting up one order

C_h = cost of keeping or maintaining one unit in the warehouse

On average, the companies had an annual demand of 373,333 BF. The average cost of setting up an order corresponding to a batch of 3,000 BF, was \$1,000. The estimated holding cost of finished goods per unit per year was between \$1.5-\$2.5 according to the incurred expenses for a 2,500 square foot warehouse per year, which is the typical square footage of the companies' warehouses. The holding cost also included capital investment, obsolescence, and damages, among others. This case only utilized the space-related holding costs. Using equation 6.1, the finished goods resulting quantity was between 22,311–17,282 BF. The cost of producing the raw material was \$450 per batch. This meant that the required inventory was between 11,593-14,967 BF. It was a noticeable decrease in inventory levels. The calculated data allows the construction of a future VSM, which is displayed in Figure 27.



	Min	Max		Min	Max
VA:	0.83	13.00	days	Lead time	23.20 42.49
NVA:	44.51	51.62	days	Process time	0.83 13.00
%VA:	1.83	20.12	%	Inventory days	22.14 28.58
%NVA:	98.17	79.88	%	Total lead time	45.34 64.62

Source: Elaborated

Figure 27. Future VSM

The total lead times obtained with the future VSM goes between 23.20 to 42.49 days. By reducing the inventory levels, the VA percentages varied from 2% to 20%; hence, the NVA percentages had a range from 98% to 80%. It is important to remember that the only VA activity of this process was the wood modification, therefore only by reducing the other activities and the inventory days was it possible to get higher VA percentages. Considering an average cost of \$1,000 to produce 3,000 BF of TMW, the inventory cost was between \$1,739 - \$2,245. And considering that it took \$450 to produce 3,000 BF of kiln-dried wood; the raw material inventory costed between \$1,738 - \$2,244 for a total inventory of \$7,500 - \$9,681 between both raw materials and finished goods.

Regarding the value of the inventory, with a selling price of \$4 per BF of TMW the value of the finished goods would be between \$69,127.90 - \$89,243.74 at a selling price of \$1.453 per BF of kiln-dried wood, the value of the raw material inventory would be between \$16,848 - \$21,751, for a total inventory value of \$85,976 - \$110,995.

Considering that the raw material inventory had an average of 73,333 BF, this represented nearly \$106,578. On the other hand, the finished goods inventory had an average of 76,667 BF, representing around \$306,668 for a total of both inventory values of \$413,244. By implementing the EOQ model with inventory levels between 11,593 - 14,967 BF and 17,282 - 22,311 BF for raw material and finished goods, it represents a savings of \$302,249 - \$327,268. Table 68 shows a comparison with the previous process and the improved process.

Table 68. Current State of Companies vs. Future VSM

	Company 1	Company 2	Company 3	Future VSM
Average batch	3,000 BF	3,000 BF	6,200 BF	3,000 BF
Raw Materials Inventory	60,000 BF	60,000 BF	100,000 BF	11,593 - 14,967 BF
Raw Material Inventory Value	\$85,250	\$87,200	\$138,833	\$1,739 - \$2,245
Finished Goods Inventory	30,000 BF	100,000 BF	100,000 BF	17,282 - 22,311 BF
Finished Goods Inventory Value	\$120,000	\$395,000	\$299,667	\$5,760 - \$7,437
Monthly demand	30,000 BF	30,000 BF	33,333 BF	30,000 BF
Lead time	55.47 days	158.69 days	151.48 days	23.20 – 42.49 days
VA	5%	8%	1%	2% - 20%
NVA	95%	92%	99%	98% - 80%
Takt time	1.75 days per batch	2.74 days per batch	4.64 days per batch	1.75 - 2.74 days per batch
Production Costs	\$1,500 per batch	\$500 per batch	Not specified	\$1000 per batch

Table 66 shows that by reducing the inventory levels for both raw materials and finished goods, the lead times and inventory costs could be improved. The VA percentages would increase while the NVA percentages would decrease.

The proposed VSM, as well as the current situation VSM of the case study companies, does not differentiate between species or if it is an open or closed system. This was why some production costs between companies varied significantly, since some species were more expensive to produce than others. In this case, it was noted that the species manufactured by company 1 are more expensive to produce than the ones of company 2.

A summary of the steps used in the construction of the proposed design is shown in Figure 28. In case any of the companies under study opt for applying the improved process strategy, there are several elements they must keep in mind. First, there must be a period to reduce excess inventory. Second, it will be necessary to invest in the EOQ model and Lean Thinking to guide the personnel involved. Using these two elements, it is possible to calculate if the project would be feasible in the following years.

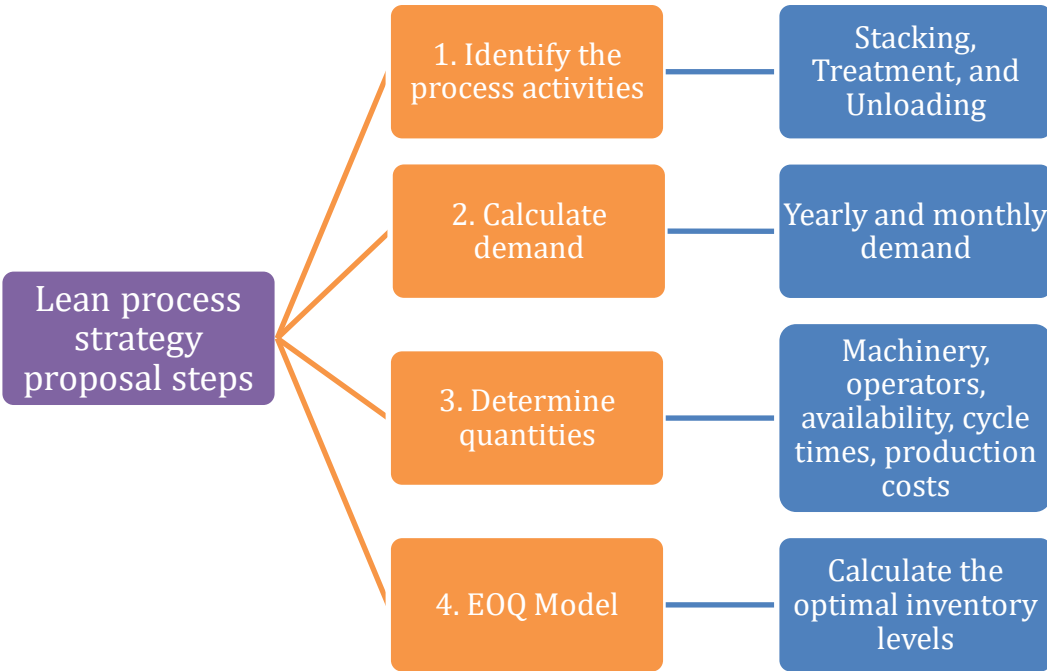


Figure 28. Lean Process Strategy construction steps

6 Conclusions

From the previous discussion of results, the author is able to summarize the main conclusions below:

- There was a significant difference in the familiarity of the respondents regarding TMW depending on whether or not they had worked with TMW products. There was a difference in knowledge for those respondents who had chosen to work with TMW.
- There were statistical differences in the familiarity of each TMW factor and the business category of the target audience. The only association was between the business category and the product pricing, where the rest of the variables studied presented no relation to each other.
- There was a lack of overall familiarity of TMW factors selected by the respondents, since more than 54% of the respondents selected “Not so Familiar” for every factor studied and fewer than 13% selected “Very Familiar.”
- The TMW factor with the most familiarity was dimensional stability with 36%, and the non-toxic aspect 32%. The least familiar factors were product pricing (18%) and species availability (18%).
- The durability of TMW products for the three species was increased compared to the values obtained from several authors treating the same fungus and wood species of untreated wood.
- The performance across the three companies was not statistically different, meaning that consumers can get TMW from a producer and expect to get similar performance from other producers.
- The hardness, MOR, MOE, and dimensional stability of yellow poplar share no statistical difference between the three companies studied. The only difference was with the EMC values for the three companies. None of the companies shared any of the mean values but, compared to theoretical values of untreated wood, the values obtained by the three companies showed an overall incremental performance for the EMC values. This incremental performance

shows that consumers can buy TMW products from producers and expect to get a product with an incremental performance of EMC.

- The MOR, MOE, and radial shrinkage values for red maple showed no difference between the companies studied.
- The tangential shrinkage, hardness, and EMC had differences between companies. Materials from company have a greater hardness values, and company 1 and 3 have similar hardness values.
- Statistical differences between the companies were found for yellow poplar, red maple, and ash regarding their EMC performance. However, when the values are compared to untreated values for each species, the improvement is significant (insert percentage improvement as a range), demonstrating that differences in values between companies is statistically significant but not practically (use of material) significant. These results were also observed in the dimensional stability of red maple and ash, where the values were statistically different, but the performance was better when compared to untreated values.
- The participating companies did not apply Lean Thinking in their thermal modification processes.
- This case study highlights the variability based on the inventory levels from the companies that produce TMW, as well as the practice to condition wood after the treatment. With the Lean process strategy designed, the effect of high inventory levels over lead times (55 – 159 days) was identified, and avoiding excess inventory levels was proposed, since it provided an improvement over the lead times (23 – 42 days). Since the industry of TMW in the U.S is new, the manufacturers must identify ways to manage their resources optimally and improve current practices, which will contribute to setting a baseline for future TMW wood.

7 Recommendations

From the previous discussion of results, the author is able to summarize the main recommendations below:

- A recommendation from the survey's results is that producers must start providing information on product installation techniques, the disadvantages of the TMW products, and start working on an environmental declaration, since most of the respondents who had worked with the product believe this a valuable marketing aspect. It was shown that most of the respondents were familiar with the dimensional stability of the product and non-toxic aspect, but the majority of the respondents were still not familiar with the strength aspects of TMW. The respondents did not know anything about the species available for use in TMW. Distributors and subcontractors of TMW products need to start providing more information to their clients regarding technical aspects of the product, since they are the primary source for architects to get TMW for their projects.
- Based on the results from the second objective, a recommendation for the producers is to keep their current schedules for the production of TMW. Each producer is using their own schedule to produce TMW products, and it was shown that for most of the testing conducted there was no statistical differentiation between the companies. This means that the product could be obtained from any of the producers and be expected to have an incremental performance on dimensional stability, EMC, and durability, and similar values for MOR, MOE and hardness. With this being said, the companies must start developing consensus for a product environmental declaration, which was also requested by the respondents of the survey.
- As for recommendations based on the process observed, the companies only had one value-adding activity. To increase this percentage, a thorough study of the stacking and unloading operations through a time and movements study must be conducted to reduce the cycle time of these activities.

- For a future project, it would be optimal to study of the costs involved during the manufacturing of TMW, making a differentiation between species, thicknesses, and types of system.
- Future studies could analyze why the architects who are familiar with TMW factors have not worked with the product or how they have gotten to know about the product performance.

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9 Appendix

Appendix A. Most populated counties on the east coast of the U.S

Connecticut	Delaware	Florida	Georgia	Maine
Bristol	Delaware State Chamber	Miami-Dade	Fulton	Maine State Chamber
Burlington		Broward	Gwinnett	
Farmington		Palm Beach	Cobb	
Plymouth		Hillsborough	DeKalb	
Wolcott		Orange	Chatham	
Maryland	Massachusetts	New Hampshire	New Jersey	New York
Maryland Chamber of Commerce	Middlesex	Hillsborough	New Jersey State Chamber	Kings
	Worcester	Rockingham		Queens
	Essex	Merrimack		Greater New York
	Suffolk	Strafford		Suffolk
	Norfolk	Grafton		Bronx
	Bristol	Cheshire		Manhattan
North Carolina	Pennsylvania	Rhode Island	South Carolina	Vermont
Mecklenburg	Philadelphia	Greater Providence	South Carolina Chamber	Lake Champlain
Wake	Allegheny	Block Island		Chittenden
Guilford	Montgomery	Charlestown		Rutland
Forsyth	Bucks	Cranston		Washington
Cumberland	Delaware	Jamestown		Windsor
Durham	Lancaster	Newport		Franklin
Virginia		West Virginia		
Fairfax		Kanawha		
Prince William		Berkeley		
Loudoun		Cabell		
Chesterfield		Monongalia		
Arlington		Wood		
Stafford		Raleigh		

Appendix B. IRB approval letter



**Division of Scholarly Integrity and
Research Compliance**
Institutional Review Board
North End Center, Suite 4120 (MC 0497)
300 Turner Street NW
Blacksburg, Virginia 24061
540/231-3732
irb@vt.edu
<http://www.research.vt.edu/sirc/hrpp>

MEMORANDUM

DATE: June 5, 2019

TO: Henry Jose Quesada, Juan Jose Gonzalez, Brian H Bond

FROM: Virginia Tech Institutional Review Board (FWA00000572, expires January 29, 2021)

PROTOCOL TITLE: Market factors that influence the consumption of thermally modified wood

IRB NUMBER: 19-509

Based on the submitted project description and items listed in the Special Instructions section found on Page 2, the Virginia Tech IRB has determined that the proposed activity is not research involving human subjects as defined by HHS and FDA regulations.

Further review and approval by the Virginia Tech HRPP is not required because this is not human research. This determination applies only to the activities described in the submitted project description and does not apply should any changes be made. If changes are made you must immediately submit an Amendment to the HRPP for a new determination. Your amendment must include a description of the changes and you must upload all revised documents. At that time, the HRPP will review the submission activities to confirm the original "Not Human Subjects Research" decision or to advise if a new application must be made.

If there are additional undisclosed components that you feel merit a change in this initial determination, please contact our office for a consultation.

Please be aware that receiving a "Not Human Subjects Research" Determination is not the same as IRB review and approval of the activity. You are NOT to use IRB consent forms or templates for these activities. If you have any questions, please contact the Virginia Tech HRPP office at 540-231-3732 or irb@vt.edu.

PROTOCOL INFORMATION:

Determined As: **Not Human Subjects Research**
Protocol Determination Date: **June 5, 2019**

ASSOCIATED FUNDING:

The table on the following page indicates whether grant proposals are related to this protocol, and which of the listed proposals, if any, have been compared to this protocol, if required.

Invent the Future

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY
An equal opportunity, affirmative action institution

Appendix C. Questionnaire



Questionnaire

Market factors that influence the consumption of thermally modified wood

Virginia Tech's Department of Sustainable Biomaterials would greatly appreciate your help in completing the enclosed questionnaire, the results of which will be used to identify the market perception of thermally modified wood.

The main purpose of this survey is to identify the barriers and drivers that are impacting the consumption of thermally modified wood in the United States.

Your responses and associated analysis would remain confidential and will only be used for this study. Only aggregated data will be used for reporting purposes.

Participation in this survey is 100% voluntary. The identity of yourself and your firm will not be disclosed in any communication regarding the results of this study.

This Research is being conducted by Juan Gonzalez, Graduate Research Assistant and Master's Degree student in the Department of Sustainable Biomaterials at Virginia Tech, Blacksburg, VA.

If you have any questions/comments about this study, please contact Juan Gonzalez by email at jjgoco02@vt.edu or by phone at +1 (747) 250-1441.

1. Demographic questions (Please check only one response for the following questions)

a. What were your gross sales or revenues for your most recent fiscal year (2018)?

- | | |
|--|--|
| <input type="checkbox"/> 0 - \$500,000 | <input type="checkbox"/> \$5 - 7.5 Million |
| <input type="checkbox"/> \$500,000 - 1 Million | <input type="checkbox"/> \$7.5 - 10 Million |
| <input type="checkbox"/> \$1 - 2.5 Million | <input type="checkbox"/> \$10 - 15 Million |
| <input type="checkbox"/> \$2.5 - 5 Million | <input type="checkbox"/> Greater than \$15 Million |

b. What has been your average sales growth per year for the past 5 years?

- | | |
|--|---|
| <input type="checkbox"/> Less than 1 % | <input type="checkbox"/> 11-15% |
| <input type="checkbox"/> 1-5% | <input type="checkbox"/> 16-20% |
| <input type="checkbox"/> 6-10% | <input type="checkbox"/> Greater than 20% |

c. Who is your target audience?

- | | |
|--|-------------------------------------|
| <input type="checkbox"/> Residential | <input type="checkbox"/> Landscape |
| <input type="checkbox"/> Institutional | <input type="checkbox"/> Commercial |
| <input type="checkbox"/> Other: _____ | |

d. What is the average distance where you provide services?

- | | |
|--|---|
| <input type="checkbox"/> 0-50 Miles | <input type="checkbox"/> 150-200 Miles |
| <input type="checkbox"/> 50-100 Miles | <input type="checkbox"/> 200-250 Miles |
| <input type="checkbox"/> 100-150 Miles | <input type="checkbox"/> Greater than 250 Miles |

e. How many years has your company been in business?

- | | |
|--|---|
| <input type="checkbox"/> 5 years or less | <input type="checkbox"/> 11-20 years |
| <input type="checkbox"/> 6-10 years | <input type="checkbox"/> More than 20 years |

10. What is the intended application that your customers use TM wood? (Select as many as you consider)

- | | |
|---|------------------------------------|
| <input type="checkbox"/> Indoor Furniture | <input type="checkbox"/> Roofing |
| <input type="checkbox"/> Flooring | <input type="checkbox"/> Decking |
| <input type="checkbox"/> Outdoor furniture | <input type="checkbox"/> Siding |
| <input type="checkbox"/> Door/window frames | <input type="checkbox"/> Mouldings |
| <input type="checkbox"/> Other: _____ | |

11. Which TM wood specie do you work with? (Select as many as you consider)

- | | |
|-------------------------------------|---------------------------------------|
| <input type="checkbox"/> Poplar | <input type="checkbox"/> Sweetgum |
| <input type="checkbox"/> Soft Maple | <input type="checkbox"/> Ash |
| <input type="checkbox"/> Red oak | <input type="checkbox"/> Other: _____ |

12. Which TM wood specie most customers ask for? (Select as many as you consider)

- | | |
|-------------------------------------|---------------------------------------|
| <input type="checkbox"/> Poplar | <input type="checkbox"/> Sweetgum |
| <input type="checkbox"/> Soft Maple | <input type="checkbox"/> Ash |
| <input type="checkbox"/> Red oak | <input type="checkbox"/> Other: _____ |

13. The projects that involved TM wood, was its use determined by the customer or by your business?

- | | |
|-------------------------------------|--|
| <input type="checkbox"/> Own advice | <input type="checkbox"/> Customer desire |
|-------------------------------------|--|

14. Regarding your answer on question No. 13, what characteristics are making them or you desire to work with TM wood?

15. What information would you like to see more regarding TM wood?

16. Any other experiences or comments related to TM wood that you are willing to share, please let us know below:

Appendix D. Ordinal Logistic Regressions

Ordinal Logistic Regression: Strength versus Business C Response Information

Variable	Value	Count
Strength	1	139
	2	94
	3	21
Total		254

Logistic Regression Table

Predictor	Coef	SE Coef	Z	P	Odds Ratio	95% CI	
						Lower	Upper
Const(1)	0.139192	0.148284	0.94	0.348			
Const(2)	2.35967	0.239432	9.86	0.000			
Business C							
Construction	0.426314	0.567478	0.75	0.453	1.53	0.50	4.66
Contractors	0.0292486	0.704987	0.04	0.967	1.03	0.26	4.10
Other	0.128802	0.309465	0.42	0.677	1.14	0.62	2.09

Log-Likelihood = -229.244

Test of All Slopes Equal to Zero

DF	G	P-Value
3	0.685	0.877

Ordinal Logistic Regression: Dimensional versus Business C Response Information

Variable	Value	Count
Dimensional	1	138
	2	82
	3	34
	Total	254

Logistic Regression Table

Predictor	Coef	SE Coef	Z	P	Odds Ratio	95% CI	
						Lower	Upper
Const(1)	0.132535	0.147785	0.90	0.370			
Const(2)	1.82838	0.198672	9.20	0.000			
Business C							
Construction	0.376991	0.559079	0.67	0.500	1.46	0.49	4.36
Contractors	0.118552	0.703941	0.17	0.866	1.13	0.28	4.47
Other	0.0864731	0.305122	0.28	0.777	1.09	0.60	1.98

Log-Likelihood = -245.022

Test of All Slopes Equal to Zero

DF	G	P-Value
3	0.505	0.918

Ordinal Logistic Regression: Pricing versus Business C
Response Information

Variable	Value	Count
Pricing	1	196
	2	46
	3	12
Total		254

Logistic Regression Table

Predictor	Coef	SE Coef	Z	P	Odds Ratio	95% CI	
						Lower	Upper
Const(1)	1.54485	0.195527	7.90	0.000			
Const(2)	3.37985	0.328538	10.29	0.000			
Business C							
Construction	-1.31814	0.557322	-2.37	0.018	0.27	0.09	0.80
Contractors	-0.907398	0.757593	-1.20	0.231	0.40	0.09	1.78
Other	-0.887491	0.348468	-2.55	0.011	0.41	0.21	0.82

Log-Likelihood = -160.957

Test of All Slopes Equal to Zero

DF	G	P-Value
3	10.158	0.017

Ordinal Logistic Regression: Species Availability versus Business C

Response Information

Variable	Value	Count
Species Availability	1	199
	2	41
	3	14
Total		254

Logistic Regression Table

Predictor	Coef	SE Coef	Z	P	Odds Ratio	95% CI	
						Lower	Upper
Const(1)	1.43256	0.188671	7.59	0.000			
Const(2)	2.99816	0.299279	10.02	0.000			
Business C							
Construction	-0.610360	0.602972	-1.01	0.311	0.54	0.17	1.77
Contractors	-0.763641	0.758084	-1.01	0.314	0.47	0.11	2.06
Other	-0.375498	0.366376	-1.02	0.305	0.69	0.34	1.41

Log-Likelihood = -162.707

Test of All Slopes Equal to Zero

DF	G	P-Value
3	2.410	0.492

Ordinal Logistic Regression: Non-Toxic versus Business C
Response Information

Variable	Value	Count
Non-Toxic	1	173
	2	56
	3	25
Total		254

Logistic Regression Table

Predictor	Coef	SE Coef	Z	P	Odds Ratio	95% CI	
						Lower	Upper
Const(1)	0.691061	0.157359	4.39	0.000			
Const(2)	2.15022	0.224614	9.57	0.000			
Business C							
Construction	0.143067	0.594434	0.24	0.810	1.15	0.36	3.70
Contractors	-0.0080936	0.751671	-0.01	0.991	0.99	0.23	4.33
Other	0.310087	0.346510	0.89	0.371	1.36	0.69	2.69

Log-Likelihood = -208.645

Test of All Slopes Equal to Zero

DF	G	P-Value
3	0.854	0.836

Ordinal Logistic Regression: Aspect versus Business C

Response Information

Variable	Value	Count
Aspect	1	161
	2	64
	3	29
Total		254

Logistic Regression Table

Predictor	Coef	SE Coef	Z	P	Odds	95% CI	
					Ratio	Lower	Upper
Const(1)	0.563332	0.154045	3.66	0.000			
Const(2)	2.06454	0.214277	9.63	0.000			
Business C							
Construction	-0.164149	0.551118	-0.30	0.766	0.85	0.29	2.50
Contractors	-0.275076	0.706764	-0.39	0.697	0.76	0.19	3.03
Other	0.0289654	0.321722	0.09	0.928	1.03	0.55	1.93

Log-Likelihood = -224.418

Test of All Slopes Equal to Zero

DF	G	P-Value
3	0.278	0.964

Ordinal Logistic Regression: Strength versus Target A

Response Information

Variable	Value	Count
Strength	1	139
	2	94
	3	21
Total		254

Logistic Regression Table

Predictor	Coef	SE Coef	Z	P	Odds	95% CI	
					Ratio	Lower	Upper
Const(1)	0.167710	0.208961	0.80	0.422			
Const(2)	2.39364	0.282174	8.48	0.000			
Target A							
Institutional	0.268679	0.345380	0.78	0.437	1.31	0.66	2.57
Landscape	0.0000001	0.529893	0.00	1.000	1.00	0.35	2.83
Other	0.164682	0.471224	0.35	0.727	1.18	0.47	2.97
Residential	-0.167295	0.304882	-0.55	0.583	0.85	0.47	1.54

Log-Likelihood = -228.769

Test of All Slopes Equal to Zero

DF	G	P-Value
4	1.634	0.803

Ordinal Logistic Regression: Dimensional versus Target A

Response Information

Variable	Value	Count
Dimensional	1	138
	2	82
	3	34
Total		254

Logistic Regression Table

Predictor	Coef	SE Coef	Z	P	Odds Ratio	95% CI	
						Lower	Upper
Const(1)	0.0312309	0.205906	0.15	0.879			
Const(2)	1.73579	0.242549	7.16	0.000			
Target A							
Institutional	0.379549	0.340305	1.12	0.265	1.46	0.75	2.85
Landscape	0.218277	0.527591	0.41	0.679	1.24	0.44	3.50
Other	0.502421	0.477861	1.05	0.293	1.65	0.65	4.22
Residential	0.0136404	0.300089	0.05	0.964	1.01	0.56	1.83

Log-Likelihood = -244.077

Test of All Slopes Equal to Zero

DF	G	P-Value
4	2.395	0.664

Ordinal Logistic Regression: Pricing versus Target A

Response Information

Variable	Value	Count
Pricing	1	196
	2	46
	3	12
Total		254

Logistic Regression Table

Predictor	Coef	SE Coef	Z	P	Odds	95% CI	
					Ratio	Lower	Upper
Const(1)	1.19462	0.250032	4.78	0.000			
Const(2)	2.98459	0.357200	8.36	0.000			
Target A							
Institutional	0.173564	0.421857	0.41	0.681	1.19	0.52	2.72
Landscape	0.240187	0.679463	0.35	0.724	1.27	0.34	4.82
Other	0.240187	0.593922	0.40	0.686	1.27	0.40	4.07
Residential	-0.149151	0.362529	-0.41	0.681	0.86	0.42	1.75

Log-Likelihood = -165.583

Test of All Slopes Equal to Zero

DF	G	P-Value
4	0.907	0.924

Ordinal Logistic Regression: Species Availability versus Target A

Response Information

Variable	Value	Count
Species Availability	1	199
	2	41
	3	14
Total		254

Logistic Regression Table

Predictor	Coef	SE Coef	Z	P	Odds Ratio	95% CI	
						Lower	Upper
Const(1)	1.12437	0.245277	4.58	0.000			
Const(2)	2.68643	0.333615	8.05	0.000			
Target A							
Institutional	0.344900	0.427697	0.81	0.420	1.41	0.61	3.26
Landscape	0.396813	0.693932	0.57	0.567	1.49	0.38	5.79
Other	0.705870	0.663318	1.06	0.287	2.03	0.55	7.43
Residential	0.0565866	0.366016	0.15	0.877	1.06	0.52	2.17

Log-Likelihood = -162.974

Test of All Slopes Equal to Zero

DF	G	P-Value
4	1.876	0.759

Ordinal Logistic Regression: Non-Toxic versus Target A
Response Information

Variable	Value	Count
Non-Toxic	1	173
	2	56
	3	25
Total		254

Logistic Regression Table

Predictor	Coef	SE Coef	Z	P	Odds Ratio	95% CI	
						Lower	Upper
Const(1)	0.672503	0.221569	3.04	0.002			
Const(2)	2.13118	0.273107	7.80	0.000			
Target A							
Institutional	0.0572673	0.362778	0.16	0.875	1.06	0.52	2.16
Landscape	0.354097	0.603479	0.59	0.557	1.42	0.44	4.65
Other	0.354097	0.527341	0.67	0.502	1.42	0.51	4.01
Residential	0.0855150	0.329701	0.26	0.795	1.09	0.57	2.08

Log-Likelihood = -208.707

Test of All Slopes Equal to Zero

DF	G	P-Value
4	0.729	0.948

Ordinal Logistic Regression: Aspect versus Target A

Response Information

Variable	Value	Count
Aspect	1	161
	2	64
	3	29
Total		254

Logistic Regression Table

Predictor	Coef	SE Coef	Z	P	Odds	95% CI	
					Ratio	Lower	Upper
Const(1)	0.450161	0.213893	2.10	0.035			
Const(2)	1.95486	0.258516	7.56	0.000			
Target A							
Institutional	0.141628	0.351885	0.40	0.687	1.15	0.58	2.30
Landscape	0.290153	0.567323	0.51	0.609	1.34	0.44	4.06
Other	0.511594	0.517146	0.99	0.323	1.67	0.61	4.60
Residential	0.0423795	0.315452	0.13	0.893	1.04	0.56	1.94

Log-Likelihood = -223.937

Test of All Slopes Equal to Zero

DF	G	P-Value
4	1.238	0.872

Ordinal Logistic Regression: Strength versus Target A, Business C

Response Information

Variable	Value	Count
Strength	1	139
	2	94
	3	21
Total		254

Logistic Regression Table

Predictor	Coef	SE Coef	Z	P	Odds	95% CI	
					Ratio	Lower	Upper
Const(1)	0.116199	0.221968	0.52	0.601			
Const(2)	2.34689	0.290719	8.07	0.000			
Target A							
Institutional	0.287835	0.346750	0.83	0.406	1.33	0.68	2.63
Landscape	-0.0418660	0.541453	-0.08	0.938	0.96	0.33	2.77
Other	0.170802	0.474041	0.36	0.719	1.19	0.47	3.00
Residential	-0.186331	0.306363	-0.61	0.543	0.83	0.46	1.51
Business C							
Construction	0.525184	0.573354	0.92	0.360	1.69	0.55	5.20
Contractors	0.0283487	0.707273	0.04	0.968	1.03	0.26	4.11
Other	0.125454	0.317302	0.40	0.693	1.13	0.61	2.11

Log-Likelihood = -228.295

Test of All Slopes Equal to Zero

DF	G	P-Value
7	2.583	0.921