POTENTIAL UTILIZATION OF U.S. HARDWOODS FOR PRODUCTION OF CLARINETS

by

Yue Zhao

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THE PURDUE UNIVERSITY GRADUATE SCHOOL
STATEMENT OF COMMITTEE APPROVAL

Dr. Eva Haviarova, Chair

Department of Forestry and Natural Resources

Dr. Henry J. Quesada

Department of Forestry and Natural Resources

Dr. Rado Gazo

Department of Forestry and Natural Resources

Approved by:

Dr. Robert G. Wagner

Head of the Graduate Program

I would like to dedicate this thesis to the hardwood lumber industry.

May this work contribute to its sustainability and prosperity.

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ABSTRACT

Author: Zhao, Yue. MS
Institution: Purdue University
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Committee Chair: Dr. Eva Haviarova

Clarinets are perfect example of musical instruments produced from tropical wood species Grenadilla (*Dalbergia melanoxylon)*, wood species which could have a suspicion origin. It is of high interest for producers and consumers to find a sustainable substitution for the currently used material for its production. Therefore, a case study was developed in cooperation with local clarinet producer to evaluate possible substitution of Grenadilla for a new material sourced from U.S. temperate forests. Specifically, a study was conducted on the production of clarinets from four U.S. hardwood species, Hard Maple, Black Walnut, Black Cherry and Yellow Poplar. These instruments were compared with clarinets made of Grenadilla and ABS (*Acrylonitrile butadiene styrene*) plastic, materials currently used for clarinet production. To improve workability (machining), wood treatment with cactus juice (Methyl Methacrylate) was also investigated. Clarinets made from U.S. hardwood species and their treatment were benchmarked with traditionally made clarinets from Grenadilla and ABS plastic. Producer and users perception surveys were conducted. Seventeen experienced clarinet testers and ten experienced players evaluated eleven different instruments. All study participants were very open to the idea of using U.S. hardwoods for production of clarinets. Instruments made of U.S. hardwoods were evaluated and graded from four perspectives: appearance & color, touch & feel, tone & sound, and overall quality. Quantitative and qualitative measures were used to assess the feasibility of proposed material substitution. Study findings are supported by statistical analysis. Based on the Tukey results, clarinet made of treated Maple was comparable with both Grenadilla and ABS plastic clarinets. Mann-Whitney results show that treated Maple was also a best substitution option in all categories when compared with ABS plastic, but when compared with Grenadilla, treated Maple was comparable only in touch/feel and tone/sound aspects. Cactus juice treatment improved material properties, especially workability, which is a very important property for the production of clarinets. In conclusion, treated Hard Maple was the most promising substitution material.
Key words: *Clarinets production; material substitutions; U.S. hardwoods;*

CHAPTER 1. INTRODUCTION

1.1 Statement of the Problem

Inappropriate sourcing of tropical wood species is causing illegal harvesting and contributing to the global deforestation (Sheikh 2010). Tropical wood species are used often for production of wooden musical instruments (Fletcher 1999). Users of these products are generally not aware of these issues and many do not realize that their musical instrument could be made of illegally obtained wood species (Johnson and Lawson 2017). For example, ebony is used for soundboards and fingerboards, rosewood is used for plates, ribs and many other components of string instruments (Sproßmann et al, 2017; Lee et al, 2015). African Blackwood (Dalbergia Melanoxylon), a high-density tropical wood species, is used for production of clarinets, because of its excellent workability (Brémaud 2012). However, the material supply of this kind of wood species is deficient and harder to obtain. The Lacy Act, a conservation law in the United States that prohibits trade of plants and plants products, as well as wildlife, and fish, that have been illegally taken, possessed, transported, or sold, is the world's first ban on trade of illegally sourced wood products (Alexander 2014; Service et al. 1900). Material and products made of endangered tropical wood species are hard to import and export even when they are obtained from sustainable sources (Bridegam and Eastin 2014).

Considering utilization of sustainable materials, the U.S. hardwood species, for production of selected musical instruments is the main goal of this project. Specifically, we are investigating the production of clarinets from four U.S. hardwood species: Hard Maple, Black Walnut, Black Cherry and Yellow-Poplar. Quantitative and qualitative measures areused to assess the feasibility of proposed material substitution. This study was conducted in cooperation with commercial clarinet producer (Con Selmer Inc. from Elkhart Indiana).

Traditional wooden clarinets are made of an African tropical wood species with the properties of extreme hardness, high density, and almost dark-black color. Usually, people call it Grenadilla, and sometimes other names, such as African blackwood, m'pingo, ebony, or the official name: *Dalbergia melanoxylon*. More affordable clarinets, commonly used by beginner players, are made of black ABS plastic (acrylonitrile butadiene styrene). Plastic instruments have many advantages, including anti-crack, the need of less maintenance, better resistance to rain, sun exposure, as well as dimensional stability upon exposure to humidity or at different temperatures, as well as slightly lighter weight in contrast with wooden instruments. Plastic clarinets are easy to recognize since their “blacker” and shinier look compared with that of wooden instruments. Even differences in performance are saddle, but clarinetists still love and prefer to play wooden clarinets, because of their richer, darker, and warmer sound and perhaps a higher status and long tradition. In general, wooden instrument can be easier to play, lasts longer, and needs fewer adjustments. Advanced and professional player usually spend more than two to three thousand dollars to buy one wooden clarinet. The most expensive clarinets cost around six thousand dollars or more. It is not always easy to tell a difference between a higher-priced clarinet and a lower-priced one from its appearance, because even cheapest instruments look good (Pinksterboer 2011).

From material standpoint, the use of tropical wood species could cause illegal harvesting, and as a result contribute to the global deforestation and cause many international conflicts. Overall, the majority of deforestation is happening in tropical forests and globally, forest area is decreasing mainly due to clearing and converting tropical forests to agricultural land. However, the hunt for precious wood species and harmful forestry practices in tropical forests historically was and still is a significant contributor to deforestation (Sampson 2005). The destruction of the world's forests is a well-known by-product of the development of modern society. Originally, 80% of Earth was have been covered by forest and then gradually cleared, fragmented or degraded by logging, mining, clearance for agriculture, or urbanization. Although increased public awareness, reforestation initiatives and improvements in air pollution levels have helped forests to recover and grow in developed countries, most of the world's forests are still located in a small number of areas – the Amazon Basin, Central Africa, South East Asia and the Russian Federation – where they are significantly threatened (Brack 2003). Forests are disappearing at the rate of tens of thousands of square miles per year. The deforestation is causing waste a valuable natural resource throughout much of the developing world and is driving countless plant and animal species to extinction. At the same time, it may have also significant effects on world climate change (Repetto 2017). Due to deforestation, some tropical wood species are now threatened by extinction and subject to trade protection under international environmental law. Under these circumstances, a number of frequently-used tropical wood species are only available to a limited extent.

Currently there are in place systems, which could prevent illegal logging, where certified wood comes from forests that documents sustainable forestry techniques (such as replanting after logging). Many certifications systems exist – FSC (Forest Stewardship Council), FAS (Foreign Agricultural Service), etc. that could help to protect the forest and slow down the deforestation. These systems are only in initial development in countries where tropical wood species for production of musical instruments usually come from, such as Congo Basin in Central Africa (Gan et al. 2016).

The Lacy Act, a conservation law in the United States that prohibits the trade of plants, plants products, wildlife, and fish that have been illegally taken, possessed, transported, or sold, is the world's first ban on trade of illegally sourced wood products (Alexander 2014). The Lacey Act is a critical tool that is attempting to combating global deforestation. The premise behind the amendment to the Lacey Act is simple-it is illegal to import and trade illegal timber. Companies must verify that they are buying their material from legal sources when they are importing wood and wood products into the U.S. For example, according to the Lacey Act, if a company is importing wood from Brazil, that wood must be harvested, and processed according to Brazilian law or it would be deemed illegal.. The Lacey Act encourages developing countries and companies to take strong steps combating deforestation. This law is informing them that they can't export to the U.S. unless their material and products are sourced legally. This type of law has emerged as a powerful motivation for countries and companies in the developing and developed world to get their acts together. It also helps countries establish rule of law and crackdown on corruption. For many countries, the forests are the frontline in efforts to address corruption and criminal syndicates. There are many stories from developing countries that show the connection between illegal logging and corruption. After all, the best way for illegal loggers to ensure that they can continue to profit is if they ensure corruption in the ranks of the police, prosecutors, and judges. By definition, their illegal act needs a breakdown in the rule of law. Illegal logging is often not driven by local small operation deforesters but rather by large international companies, which find willing accomplices within the local governments (Perlin 1989). In many countries, there is a strong connection between illegal logging and criminal syndicates, which is called in several countries "conflict timber".   So, efforts to curb illegal logging also undermine these criminal syndicates and the destruction that they cause. Lacey Act is an important law, supported by diverse groups, which must not be undermined. Global deforestation is a major environmental, social, economic, and legal challenge in the developing world. The amendment to the Lacey Act passed with bipartisan support in 2008, is a powerful tool in efforts to stop the destruction of the world's forests (NRDC 2018).

For example, for violation of Lacey Act in 2011, the Gibson Guitar plant in Nashville, TN made shockwaves through the music world and the raid culminated in the confiscation of illegally harvested ebony and rosewood (Black 2013). Because of the Lacey Act implementation, material and products made of endangered tropical wood species are hard to import and export. Musical instrument industry will be even more seriously affected by this action, since some producers are relying heavily on these resources.

Wooden clarinets are perfect example of musical instruments produced from tropical wood species (Grenadilla – African Blackwood), wood which could be in some cases targeted as unsustainable material (Knight 2008). Many producers of musical instruments, including producers of wooden clarinets, are faced with a challenge to find a new sustainable material substitution for their future production. After few discussions, a case study was designed and conducted with the local producer of clarinet, where potential substitution of traditional material for locally sourced materials was considered. Specifically, the feasibility of clarinet production from four U.S. hardwood species, Hard Maple, Black Walnut, Black Cherry and Yellow Poplar, was investigated. These four hardwood species were compared to Grenadilla (*Dalbergia melanoxylon)* and ABS plastic, separately. To obtained comparative material properties with tropical wood species like Granadilla, several densification wood treatments were research. Treatment with cactus juice (Methyl Methacrylate) was selected and tested. Upon acquisition of the final clarinets produced by industrial clarinet producer from these four hardwood species and their treatment, producer and consumer perception surveys were conducted with professional clarinet testers, organized by the company, and band players, members of Purdue Orchestra and Marching Band. Evaluators graded instruments by: appearance/color, touch/feel, tone/sound, and overall quality. Quantitative and qualitative measures were used to assess the feasibility of proposed material substitution and their outcomes are described in results section in this thesis.

1.2 Objective and Goals

Main Objective: To assess feasibility of substituting tropical wood species with the U.S. hardwood species for the production of clarinets.

Goal 1: Select suitable U.S. hardwood species for production of clarinets.

Goal 2: Investigate possibilities of material treatment for properties improvement to make it comparable with Grenadilla.

Goal 3: Address workability and possible clarinet production from selected U.S. hardwood species and their treatments.

Goal 4: Assess the consumer acceptance of clarinets made of U.S. hardwoods and benchmark them with traditional instruments.

1.3 Hypothesis

(Ho): It is possible to substitute endangered tropical wood species used in production of clarinets with U.S. hardwoods.

CHAPTER 2. BACKGROUND (LITERATURE REVIEW)

2.1 Importance of U.S. Hardwoods and the American Hardwood Industry

The U.S. has about 8 percent of the world's hardwood forest, which are mainly located in the East of USA; from Maine in the North to the Gulf of Mexico in the South, and westwards across to the Mississippi valley (FAO 2017, AHEC 2017). The U.S. hardwood regions could be seen on map in Figure 2.1 (AHEC 2017). The majority of the hardwood forestland within the U.S., approximately 79 percent, is privately owned. Most of the landowner own forests in small tracts of average size less than 10 ha. These individual landowners provide approximately 92 percent of the fiber needed to support the hardwood forest products industry. The remainder of the hardwood forestland is owned by federal (12%), state and municipal governments (9%) (USDA Forest Service 2011). The U.S. hardwood grows in uneven aged stands, where trees of varying ages grow together. Harvesting is usually by singletree selection. Regeneration of hardwood forest occurs naturally. The U.S. hardwood species are growing at a far greater rate than they are harvested. Hardwood growth to removal is 2.4 to 1 (304 million m^3 growth; 128 million m^3 removals; 109 million m^3 mortality) (USDA Forest Service 2011).

2.1.1 Sustainability of the U.S. Hardwood Forest

The hardwood forests of North America support a vibrant and healthy stand of timber. Few other countries can talk about the success North America has had in the sustainability of its hardwood forests (AHEC 2017, Oversteegen et al. 1999). Private landowners have shown widespread adoption of sustainable forest management practices, including forestry best management practices (BMPs). BMPs are very effective science-based guidelines for harvesting forests, which have the flexibility to be regionally adaptive(AF&PA 2016). "Sustainable forest management involves practicing a land stewardship ethic that integrates silviculture (reforesting, managing, growing, nurturing and harvesting of trees for useful products) with the conservation of soil, air and water quality, wildlife and fish habitats, recreation and aesthetics. Sustainable forest management practices on the U.S. forests ensure healthy and abundant forests for present and future generations, while providing renewable material for the production (AF&PA 2016)."

2.1.2 The U.S. Hardwood Forest Products Industry

The American hardwood industry, which dates back to the first European settlers, has a wealth of experience in sourcing and processing the native hardwoods of North America (AHEC 2017). The U.S. primary hardwood industry, is the largest producer of sawn hardwood in the world and it depends heavily on this resource. In recent years, the U.S. is substantially increasing its export but through careful management of its forests, the United States is growing more hardwood resource each year than it harvests and ensuring long term supplies. As the world faces many environmental challenges in area of sustainable material supply, the good news is that the net volume of hardwood growing stock in the USA has increased at least two fold (from 184,090 million cubic feet in 1953 to just under 400,000 million cubic feet in 2007) (Resource Planning Act Assessment 2007; AHEC 2017).

2.1.3 Available Hardwood Species

The hardwood forests of the Eastern United States contain a wide range of temperate hardwood species, which have been managed for commercial and non-commercial purposes since the turn of the 20th century. The USA has more temperate hardwood species than any other region of the world (AHEC 2017). However, the quality of hardwood timber varies considerably by the region. The Northern and East Central regions contain the greatest volume of high quality hardwood resource (Luppold and Pugh 2016). The U.S. hardwoods manufacturers and end-users around the world use a great variety of wood species with interesting colors, grains and character marks; from the warm, darker tones of walnut, red alder, elm, cherry and red oak to the lighter hues of white oak, maple and ash (AHEC 2017).

Commercially available wood species are: Alder, Ash, Basswood, Birch, Beech, Cherry, Cottonwood, Hickory, Soft & Hard Maple, Red and White Oak, Yellow Poplar and Walnut. Lesser-known species are: Red Elm, Grey Elm, Sassafras, Butternut, Coffee tree, Sycamore, and Hackberry (Pike Lumber Company). Most of these species can be used for a wide range of applications and high value products such as: hardwood lumber, sawn lumber, sliced veneer, veneer logs, specialty logs, wood components, and flooring, furniture, architectural elements, and more (AHEC 2017). There is a great potential for new products to come since the U.S. hardwood resource is abandoned and sustainable.

In conclusion, same as other parts of the world, North America went through the historical deforestation, as country developed, however that is not the case for the last century. Approximately 766 million acres in the U.S. land is forestland - the same acreage that existed 100 years ago. This is due, in part, to reforestation efforts, improvements in agricultural practices and forest products markets, which are environmentally and economically sustainable. While deforestation is still occurring in other parts of the world, there is more standing wood on the U.S. forestlands today than there was a half century ago (AF&PA 2016). Illegal logging and timber theft occurs also throughout the world. In 2005, AHEC commissioned Seneca Creek to study illegal logging in the U.S. They found that illegal logging in the U.S. is almost non-existent (less than 1%) and determined that forest products from the U.S. to be very low risk of being from illegal sources. There is also a growing concern that the U.S. hardwood resource is now being severely underutilized (UN Forest Products Market Review 2010). The aim of this project is to investigate the opportunity to utilize the U.S. hardwoods for anther applications, for production of value added products such as musical instruments. Specifically, we are addressing production of clarinet and potential substitution of endangers tropical wood species with the U.S. hardwoods.

2.2 Overview of Musical Instrument Made of Wood and their Manufacturing

2.2.1 Musical Instruments Made of Wood

Type of musical instruments and wood species used for wooded musical instruments are summarized in this section. The musical instrument may vary diversely in its forms and functions. In the past centuries, thousands of diverse instruments and their variants have been seen within the fundamental categories, including wind, string, and percussion (Metmuseum 2018), let alone electronic inventions in more recent time. The basic categories of musical instruments and material used for production of selected wooden musical instruments and their components are listed below. Endangered tropical wood species commonly used for these instruments are bolded (Newworldencyclopedia 2018).

a) Strings

Violin: Spruce for the top, Maple for the back, sides and back

Guitars: **Ebony, Rosewood**, Spruce, Cedar, Mahogany for the back, sides and tops

Luthiers: Poplar for the back and sides

Fiddlers: Maple, Spruce for soundboard

b) Percussion

Drums: Birch, Maple, **Mahogany**, Oak, Beech for the shell

Piano: Birch, Maple, Fir, Oak, **Mahogany, Ebony**, Spruce and other exotic woods

c) Aerophone

Flute: **African Blackwood, Cocus wood, Honduran Rosewood**, Tulipwood, Maple

Accordion: Oak

Clarinet: **African Blackwood, Cocus wood, Rosewood,** Boxwood, etc.

d) Xylophone

Marimba: **African Padauk** and **Rosewood**

Production of clarinet was selected for the case study of this thesis.

2.3 Clarinet Production

2.3.1 Background & Raw Materials

As a woodwind instrument, the clarinet possesses various sizes and different pitch ranges and should be played with a single reed. A standard clarinet consists of five basic components, including the mouthpiece, the barrel or tuning socket, the upper (or left-hand) joint, lower (or right-hand) joint, and the bell. The body is mainly made of wood. The heavy and dark wood, African Grenadilla wood or Blackwood (*Dalbergia melanoxylon*) has long been the most popular wood material in clarinet production because it endows clarinets with characteristic color. Another heavy dark wood that is also popular in clarinet production is Ebony (*Diospyros melanoxylon*), which comes from Africa. Despite the fact that Cocus (*Byra ebanus*), Boxwood (*Buxus sempervirens*) and various types of Rosewood (*Dalbergia nigra*) are rarely used today, they were very popular to be used for clarinet making in the past. Some of clarinets were found to be made of ivory. Both, ebony and Ebonite (hard rubber), were exploited by French makers in clarinet making in the mid-nineteenth century. In spite of similar density, Ebonite shows superiority in its lower price and better proof-cracking feature in contrast with Grenadilla. Apart from the materials mentioned hereinabove, a large number of synthetic materials including plastic, graphite and porcelain are also adopted in clarinet production. Even hard rubber was used for clarinet processing in the past, but still can be found in low-quality instruments today. However, African blackwood was regarded as the preferred material gradually, due to its similarity to ebony but with less heavy and less brittle features (Knight 2008; Hoeprich 2008). The keys are usually made out of an alloy called German silver, which is made from copper, zinc, and nickel with the similar appearance of pure silver and no tarnish. Some fine instruments are made with pure silver or gold-plated keys. The key pads require cardboard and felt or leather. The reed is made from cane. Other materials used in the clarinet are cork and wax for lining the joints, and a metal such as silver or a cheaper alloy for the ligature, the screw clip that holds the reed in place, and stainless steel for the spring mechanisms that work the keys (Ding, Koubaa, and Chaala 2013; Geoffrey 1971; Trevor 1980).

2.3.2 The Manufacturing Process

a) Wooden Models

When the wood is harvested for clarinet-making, logs are sawed into length between 3-4 ft (1-1.2 m) firstly and then seasoned by being kept in the open air for several months or dried in a kiln to prevent later warping. Those logs should be split and sawed to the lengths approximating the finished lengths of the clarinet body pieces, (upper and lower joints, barrel and bell). The body pieces look like narrow rectangular blocks, and pieces for the barrel are carved in a rough pyramidal shape, which are known as billets. The manufacturer buys the billets in lots, and begins the manufacturing process from these roughed-out shapes (Ding, Koubaa, and Chaala 2013; Geoffrey 1971; Trevor 1980).

Upon the receipt of billets by the manufacturer, an inspection of the lot should be performed. Then, the billets need to be placed on a borer and a hole should be drilled lengthwise through the center of each piece. The diameter and shape of this hole, called the bore of the clarinet, is of great essentiality to determine the tone of the instrument. The bore may be drilled in a straight cylinder, which may be slightly tapered. After the bore is drilled, the body pieces are turned on a lathe. The rectangular billets become smooth, round, hollow cylinders and then are seasoned again (Ding, Koubaa, and Chaala 2013; Geoffrey 1971; Trevor 1980).

After being seasoned for the second time, the rough pieces should be reduced to the finished size, turned on a lathe and trimmed to exceedingly precise diameters. The joints where the body pieces fit into each other are turned upon the completion of the exterior. The bore may be reamed more precisely and then polished on the inside. Then, the joints are painted with a black dye (Ding, Koubaa, and Chaala 2013; Geoffrey 1971; Trevor 1980).

b) Plastic Models

Body parts for clarinets made of plastic (ABS type) are produced by injection molding. Plastic pellets are melted and forced under pressure into molds. The molds for clarinet body parts produce hollow cylinders. In some cases, due to the preciseness of the molds, there is no need to make any additional reaming for these cylinders; or they may be reamed and polished just like wooden clarinets. The steps that follow are applicable to both wooden and plastic models (Ding, Koubaa, and Chaala 2013; Geoffrey 1971; Trevor 1980).

c) Boring the tone holes

Next, the tone holes that the player cover with his fingers should be bored by the maker so as to make the different notes. The most common method for mass-produced clarinets is to set the body pieces in a setting out machine. Then, a table is used to hold the piece on a mount under a vertical drill. The holes are drilled at specified distances apart and with precise diameters. The tuning of the instrument is affected by the exact dimension of the holes affects; and the holes may be adjusted after the instrument is nearly complete. Since the hole may vary in their sizes, the maker may have to insert a different drill bit for each hole. The holes are smaller on the outside than on the inside; what’s more, the holes should be undercut to achieve their precise shape upon drilling. A small and flared tool is used by the clarinet maker and placed in the tone hole to expand the underside of the hole. Tiny holes that are next to the tone holes and used for holding the key mechanism are also drilled. This may be a step in the production of instrument where material properties could make a significant difference (Ding, Koubaa, and Chaala 2013; Geoffrey 1971; Trevor 1980).

d) Construction of Keys

Hand-forged keys were deployed to make early clarinets; while, die-casting is usually used as the modern method. Molten alloy is forced under pressure into steel dies. A group of connected keys may be made in one piece in this method. Alternately, individual keys may be stamped out by a heavy stamping machine, and then trimmed. These individual keys are then soldered together with silver solder to make the connected group. Next the keys are polished. Keys for inexpensive models may be placed in a tumbling machine, where friction and agitation of pellets in a revolving drum polish the pieces. More expensive keys may be buffed individually by being held against the rotating wheel of a polishing machine. Some keys may be silver-plated, and then polished (Ding, Koubaa, and Chaala 2013; Geoffrey 1971; Trevor 1980).

The keys are then fitted with pads that are usually made of several layers - cardboard, felt, and skin or leather. The circular pads are stamped or cut, and then workers glue them by hand into the head of the key. This will muffle the sound of the tone hole closing when the instrument is played. The keys are drilled, and then fitted with springs that will keep them either open or closed. These springs are made of fine steel wire (Ding, Koubaa, and Chaala 2013; Geoffrey 1971; Trevor 1980).

e) Mounting the Keys

The keys are mounted on small pillars called posts that are first set in the holes previously drilled for them. In many models the posts are threaded and can be simply screwed in by hand. Tiny holes are then drilled by using a very small drill bit in the posts to hold the needle springs. Then the keys are screwed into the posts with stainless steel hinge rods. The assembler uses a fine screwdriver, pliers, and a small leather mallet to fit the keys and adjust the spring action. The assembler also makes an inspection to see whether the tone holes are covered completely by the key pad, inserting a tiny pick under the pad on each side. The pad may need to be adjusted or reset, or the assembler may clamp a key shut temporarily, to set the crease for a perfect, airtight closure (Ding, Koubaa, and Chaala 2013; Geoffrey 1971; Trevor 1980).

f) Finishing

The joints of the body pieces are lined with cork and waxed, so that the pieces fit smoothly into each other. The ends of the body pieces are fitted with decorative metal rings as the bottom of the barrel. The barrel is usually embossed with the name of the maker. The mouthpiece, manufactured separately out of hard rubber, is fitted to the instrument. When a reed is inserted, the instrument can be played for the first time (Ding, Koubaa, and Chaala 2013; Geoffrey 1971; Trevor 1980).

g) Quality Control

After the clarinet is fully assembled, an inspection of the instrument for visual flaws as well as the action of the keys should be made by a worker, and then the instrument should be played to perform a test. The worker can note the tone quality, intonation, and action of the new instrument through playing it (Ding, Koubaa, and Chaala 2013; Geoffrey 1971; Trevor 1980). The finished clarinet should be checked for precision tuning. The clarinet's sounding A natural should be at 440 cycles per second, and the other notes in tune with this. If the instrument has been manufactured according to a standard model, with care to exact diameters of bore and tone holes, it should play in tune automatically. It may be tested with an electronic tuner, and the diameters of the tone holes made larger by more reaming, if necessary. If tone holes are too large (producing a flat note) they may be filled with a layer of shellac (Ding, Koubaa, and Chaala 2013; Geoffrey 1971; Trevor 1980). The wood of the clarinet body should not crack, and the action of the keys should be smooth and not too loud. Ideally, the instrument should last for decades without warping, cracking, or any serious defect (Ding, Koubaa, and Chaala 2013) (Ding, Koubaa, and Chaala 2013; Geoffrey 1971; Trevor 1980).

2.4 Wood Densification

Because properties of the U.S. hardwood species are not comparable with properties of tropical wood species traditionally used for production of clarinets, wood densification treatments were considered. In general, the density of the wood material is dependent on the cell wall thickness and size of lumen. Density of wood could be increased by reducing the void space which could be reduced by chemical processes, filling the lumen with a resin or other chemicals (M. Seborg, Tarkow, and Stamm 2010), or mechanical processes, by compressing the wood structure under suitable moisture and temperature without adding any chemicals to the process. A typical after-treatment, to fix the compressed state, is the thermal modification (TM). This reduces setrecovery, which is a significant issue for the usability and stability of densified wood. Wood densification and its performance is broadly investigated (Fang et al. 2012; Kutnar and Šernek 2007). Several densification methods are out there, for example: Thermo-hydro-mechanical (THM) treatment, which is the surface densification method used mainly for densification of fast grown and low-density wood species. It is one of the promising techniques for broadening the application of these species. The surface densification process starts with relatively dry wood. Prior to the actual densification, the surface of wood is softened and then compressed using friction, heated platens, or both. This method is used for manufacturing of high-density wood laminates. (Sadatnezhad et al. 2017). However, for production of musical instruments, bulk (throughout) densification method is needed. Viscoelastic thermal compression (VTC) is one of the bulk densification methods, where wood material is usually water saturated, and then compressed. This process requires a long processing time (Rautkari et al. 2010). For densification with adding chemicals, we considered cactus juice - Methyl Methacrylate (MMA) wood treatment, which should improve material workability and dimensional stability of treated material (Rowell and Konkol 1987). Cactus juice treatment is used often for wood products, which are exposed to the moisture. Clarinet is a wind instrument and by blowing the air in it, it is exposed to the moisture. This product could benefit from MMA treatment, which would stabilize the material instrument is made of. Furthermore, investigation of cactus juice treatment was selected because of its feasibility with respect to application, time, and required equipment.

2.4.1 Treatment with Cactus Juice (Methyl Methacrylate / MMA)

Wood stabilized with methyl methacrylate (MMA) is used by manufacturers of knives, pool cues, jewelers, and manufacturers of decorative pens, among others to enhance the appearance of the wood and to eliminate or reduce the degradation of the wood by repeated wetting and drying (Mclvor 2014). Treatment of wood with MMA will endow the wood surface with a lustrous appearance, which may be enhanced by sanding with very fine sandpaper. The wooden handles of cooking utensils are also treated with MMA to avoid contamination of foodstuffs with bacteria that would otherwise propagate in untreated wood. Small wooden object such as pens are often treated with methyl methacrylate to enhance their appearance (Roger M. Rowell and Konkol 1987; Technology 2006). Because high density and workability play an important role for easy clarinet production, decision was made to treat subgroup (half) of all specimens with cactus juice. Half of specimens were kept natural and untreated.

Cactus juice is a heat cured resin used to harden and stabilize most porous material, especially wood. It comes pre-activated in pints and quarts and ready to activate with the activator in project appropriate size vessel (TurnTex 2009). It has been noted during treatment of various wood species that treating for example walnut may discolor the mixture and make it unsuitable for use with other lighters wood species. The ultimate goal of the treatment with MMA is to fill void spaces existing within the wood (Mould 2000).

As a sort of liquid without any color, MMA can boil under the temperature of 212 °F (100 °C). Prior to application of MMA for wood treatment, the wood should be positioned in a vacuum chamber for removal of air from the wood structure. Although the wood is still in the vacuum state, introduction of adequate quantity of MMA (along with a cross-linking agent and catalyst) is needed to cover the wood. Then, the vacuum will be released and the wood should be soaked with MMA. Soaking duration rests with the wooden structure (Rowell and Konkol 1987). Upon the completion of saturation, the wood-monomer composites should be removed, sometimes wrapped in aluminum foil and put in an explosion-proof oven or a cobalt-60 source for curing. A free radical catalyst is also a requisite during the heating process. Heating duration may vary greatly under different temperatures of the oven, at least above 140 °F (60 °C). As a consequence, these wood-plastic composites can have as high as 160 percent weight gain of MMA. The polymer is nearly wholly positioned in the lumen; only a few are located in the cell wail. Consequently, MMA wood has good features in water repellency, with its stability in dimension being merely appropriately 10% (R M Rowell and Konkol 1987). The specific gravity of the composite is about 1. It can be buffed to a high polish without varnishing; once scratched, the surface is able to be re-processed since the polymer is positioned across the thickness of the wood. Addition of a dye into the monomer treating solution will result in the variation of MMA woods in colors. Application of dye is feasible over the treated wood.

Properties of MMA - Great improvements have been seen in the mechanical properties of MMA wood, in contrast with the same untreated wood species. Improvements ranging from 100% to

200% are achieved in the terms of tensile (both parallel and perpendicular to the grain), impact bending and compression strength, and modulus of rupture as well as hardness. MMA can make the wood harden and the moisture absorption rate decrease (Ding, Kaubaa, Chaala 2012). MMA wood is sold in various trade names, such as Acrylic wood, Perma-Grain, and methyl methacrylated-wood plastic composite. Extensive researches have been conducted in many countries including Europe, Japan, Taiwan and New Zealand using styrene as the monomer alone or in combination with methyl methacrylate for saturation. The resultant products are known as Lignomer in Poland or like Aploid in Japan (Rowell and Konkol 1987). MMA was used for treatment of Hard Maple inlays. It is capable to increasingly harden the wood and enhance its moisture absorption rate (Seborg, Millet, and Stamm 1956; Rowell and Konkol 1987; Rowell 2006; Petterson 1984).

There are several variations of MMA treatment. The most commonly used methods of MMA treatment include:

a) Soaking the wood in MMA;
b) Submerging the wood in MMA in a vacuum pot, applying and holding a vacuum, and then releasing the vacuum;
c) Submerging the wood in MMA in a pressure pot, applying and holding pressure, and then releasing the pressure;
d) Submerging the wood in MMA in a pressure pot, applying and holding a vacuum, releasing the vacuum, applying and holding pressure, and then releasing the pressure.

Of these four methods, soaking is the simplest but not as effective as others (Museum 1995). Basically, the treatment of wood with MMA consists of infusing the wood with liquid MMA resin and then heating the treated wood in an oven in order to cure (harden) the resin. The steps in processing the wood treatment include: a) dry the wood to be treated to a low moisture content; b) treat the wood with MMA; c) wipe excess MMA from the specimen, and wrap the specimen in aluminum foil; d) cure the wrapped specimen in an oven set at 205 degree F for 1 to 3 hours; e) remove specimen from the oven and cooling them before further processing. Treatment with MMA was investigated as an option for enhancement of the U.S. hardwoods and their use for production of clarinets.

Figure 2.1 *The U.S. hardwood regions map*

CHAPTER 3. MATERIALS AND METHODS

Production of clarinet made of the U.S. temperate hardwoods and their treatments was selected as a case study for this thesis. Tropical wood species Grenadilla (*Dalbergia melanoxylon*) is commonly used for traditional production of clarinet, as well as ABS plastic, for more affordable clarinets used by beginner players (Hal Leonard Corporation 2011). Collaboration was formed with the local clarinet producers (Con Selmer. Inc., Elkhart IN) and agreement was made that company would consider the possibility of producing clarinets from alternative wood species. Testing the use of selected U.S. wood species from local temperate forests was proposed and agreed upon. This section elaborates: material selection for the study, material treatments, description of specimen geometry pertinent to the clarinet manufacturing, sample preparation, sample evaluation by producer, and produced clarinets evaluation by surveying clarinet testers and players.

3.1 Materials

Musical instrument evolved throughout the ages and its development depended on the material availability. It is of a great interest to examine dependable and sustainable material sources suitable for production of specific musical instrument and to find out how they could limit or improve the instrument performance. For the purpose of this study, possible substitution of traditional material Grenadilla (*Dalbergia melanoxylon*) with selected wood species from U.S. hardwood temperate forest was investigated. Because the main objective of this project is to find interesting uses for hardwood species from temperate forest, following wood species were selected as the potential substitution for tropical wood species used for production of clarinets: Hard Maple, Black Walnut, Black Cherry, and Yellow Poplar. Since well performing and traditional wood species for production of clarinet is Grenadilla, the goal is to find wood species with comparable properties, such as: interesting color, high density, and the most importantly, good workability/machining (Almeida and Hernández 2006). For direct comparison, mechanical and physical properties are shown in the Table 3.1 and working properties are shown in the Table 3.2.

3.2 Description and Properties of Selected Wood Species

Maple, hard (*Acer Saccharum),* called also sugar maple, with creamy-white sapwood and darker color heartwood, the wood has the strong and hard wearing features, indicating its great resistance to abrasion and wear, as well as outstanding steam bending properties. Hard maple dries slowly with a large shrinkage, so it can be susceptible to movement due to the changes in moisture. It machines well, turns well, glues satisfactorily, and can be stained and polished to an outstanding finish. Pre-boring is recommended when nailing and screwing (AHEC 2017, Alden 1995). The wood is harder to work with than softer woods, and has high nail-holding ability. It was selected for the study because of its contrasting light color, high density and good workability/machining properties.

Walnut, black (*Juglans nigra*), with interesting rich, darker color and mild, yet visible texture. It is heavy, hard, strong, and stiff wood. Black Walnut works well with hand or machine tools. It nails, screws and glues well, it holds paints and stains very well and can be polished to an exceptional finish. It performs best when dried slowly, reducing the opportunity for degrading. Walnut has also good dimensional stability (AHEC 2017; Wiemann 2010). It was selected for the study mainly because of its interesting dark color and gentle texture.

Cherry, black (*Prunus serotina*), had interesting, rich, reddish darker color, and mild, yet visible texture. Cherry is easy to machine. It nails and glues well and when sanded, stained and polished, it produces an excellent smooth finish. It dries quickly with moderately large shrinkage, but is dimensionally stable after kiln drying (AHEC 2017; Wiemann 2010). It was selected for the study because of its interesting reddish color, good workability and machining.

Yellow-poplar (*Liriodendron tulipifera*), also known as tulip-poplar or tulipwood. It is a versatile wood that is easy to machine, plane, turn, glue and bore. It dries easily with minimal degrading. It has very good dimensional stability and has little tendency to split when nailed. It takes and holds paint, enamel and stain exceptionally well (AHEC 2017, Wiemann 2010). This wood species was selected because of its easy workability and possibility of easy treatment with stains to obtain any possible color. In our study, blue dye MMA treatment was tested on Yellow Poplar specimens.

Grenadilla *(Dalbergia melanoxylon),* is dark, almost black, tropical wood species of very high specific gravity. It is difficult to process with hand or machine tools, with an extreme blunting effect on cutters. Grenadilla is often used in turned objects, where it is considered to be among the very finest of all turning wood species, holding very well threads and other details. This wood is typically processed on metal-working equipment when made into clarinet or oboe bodies. It has a reputation as being metal-like in some of its working properties (Eric Meier 2015).

ABS Plastic, plastic clarinets are made of acrylonitrile butadiene styrene (short for ABS). ABS combines the strength and rigidity of acrylonitrile and styrene polymers with the toughness of polybutadiene rubber. Production cost of ABS plastic is roughly twice the production cost of polystyrene, but it is considered superior for its hardness, gloss, toughness, and electrical insulation properties. ABS is an opaque thermoplastic and amorphous polymer. “Thermoplastic” (as opposed to “thermoset”) has to do with the way the material responds to heat. The specific gravity of this material is 1.02, a very comparable value to traditionally use material Grenadilla (Varatharajan et al. 2011).

3.3 Methods

3.3.1 Description of Specimens Geometry

Geometry and number of wooden components needed for production of clarinets used in the study are described and illustrated in Figure 3.1 and Table 3.3. Parts for four instruments from each wood species described above were prepared. Half of material was kept natural and another half was treated with MMA.

3.3.2 Sample Preparation

Material for the study was obtained from local lumber producer (Pike Lumber Company, Inc.) from commonly prepared stock of lumber. Thicker stock of material was needed, 3 inches thick boards for production of bells and 1.5 inches thick boards for production of cylinders. Material was kelp in the controlled condition of 6 % MC before cutting.

Rectangular blocks, shown in Figure 3.2, were cut at the Wood Research Laboratory (WRL) and shipped to the clarinet producer (Con Selmer, Elkhart, IN) for further processing. Roughed-out components of two shapes: rough hollow cylinders and rough pyramidal shape bells shown in Figure 3.3 were processed by clarinet producer and send back to the WRL for observation and treatment. Once specimens were visually observed and half of them treated by cactus juice, they were send back to the producer for further processing into finished components – smooth, round, hollow cylinders, and bells are shown in Figure 3.3.

3.3.3 Treatment

Three different treatments were applied: a) half specimens were kept natural; b) second half was treated by Methyl Methacrylate (MMA or cactus juice); within this treatment, coloring (blue dye) was added to MMA for a small specimen subset.

Treatment process by MMA (cactus juice) was described with details in literature review. Method selected was: submerging the wood in MMA in a pressure pot, applying and holding the vacuum, releasing the vacuum, applying and holding pressure, and then releasing the pressure.

Natural treatment – Hard Maple, Black Walnut, Black Cherry and Yellow Poplar, half of specimens of these four species were just machined but not treated. Those untreated and rough-cut wood samples are shown in Figure 3.4.

Cactus juice treatment (MMA treatment) – vessel was filled by MMA (Methyl Methacrylate). Because of improvement in safety, glass vessel was upgraded to a plastic vessel and was used for the majority of treatments. Specimens were treated under high pressure and high heat for four to five hours. After additional soaking, they were wrapped in aluminum foil and baked in the oven for two to three hours (Mclvor 2014; Roger M. Rowell and Konkol 1987). The process is shown in Figure 3.5.

Blue dye treatment – a blue dye was added to MMA treatment for a small subset of specimens within treated group to obtain an interesting and innovative color. The rest of the treatment process was the same as one without dye. The process is shown in Figure 3.6.

3.3.4 Visual Observation of Specimens and Machining Properties

Visual observation of specimen surface was conducted by investigators prior to the treatment. Second observation of specimen surfaces was conducted by the producer after final specimens machining. Assessment of workability by the producer is recorded in Table 3.4.

Final machining (tapping holes, sanding, polishing) and assembly of final products was the next production step. During this step, producer selected only those specimens, which performed well after all needed machining. Many specimens were excluded from the study mainly due to a low performance during taping holes. This is documented in number of parts and number of competed instruments in Table 3.3.

For control, two traditional instruments were produced and added to the study for benchmarking purpose, one from ABS plastic and other from Granadilla. Detailed production process of final clarinet production is described in literature review section. There were no adjustments made to the production process when new type of material was used. All processes remained the same as it is used for production of Grenadilla instruments.

3.3.5 Survey

Produced instruments were evaluated by three groups: by two members of in-house professional testers; by 15 other clarinet testers outside the company; and by 10 professional clarinet players from university band and orchestra.

3.3.5.1 Survey Design

The survey was design to collect consumer perception, as well as to benchmark clarinets made of alternative wood species (U.S. hardwoods) with traditional clarinets made of Granadilla and ABS plastic. Survey was developed by investigators with the detailed and constructive input from the clarinet producer. It was designed as a tool to efficiently collect feedback on the instrument attractiveness and performance. Survey is included in the appendix section of this thesis (Appendix A).

Participants of this study express their attitudes towards clarinets made of the U.S. hardwoods plus two traditionally made clarinets, one from Grenadilla and other from ABS plastic. These two instruments were included in the study as a control. The survey consisted of five sections:

a) Demographic data on the respondents, including age and gender;
b) Questions about participants' musical experience, such as proficiency level of playing clarinets and ability to play other instruments;
c) Each clarinet was evaluated from four different aspects, including: appearance/color, touch/feel, tone and overall quality;

d) Question was asked if participants are willing to purchase tested clarinet;

e) General comments about each clarinet were also collected and evaluated.

During the testing process, nine clarinets made from the U.S. hardwoods and two traditional clarinets (Grenadilla and ABS plastic) were presented to each participant. Clarinet material was not identified for the participants during the surveying process. They were asked to grade each clarinets, one at the time, from four different aspects: Appearance/Color, Touch/Feel, Tone and Overall Quality. Each score was on the scale 1 to 5 level (5 is the best score).

Different surveying methods were considered but for this study, the 5-point Likert scale was applied as an instrument for structuring and analyzing the answers, as previously used in related research in this field (Gossling et al. 2005; Ek 2005; Qu et al. 2009). Each aspect for each clarinet was measured in survey using the 5-point scale as follows: 1 (strongly disagree), 2 (disagree), 3 (not disagree, not agree), 4 (agree), 5 (strongly agree). The reliability of the 5-point Likert scale in the survey research was tested by using the Cronbach's alpha which showed a highly satisfactory level of internal consistency, which is above 0.90. A reliability coefficient of 0.70 and above is usually considered acceptable and desirable for consistency levels (Nunnally and Bernstein 1994).

3.3.5.2 Participants and the Data Collection

The survey was conducted in three stages: a) by two in house highly trained clarinets testers (during July 2018). Both testers are also good clarinet players; b) by fifteen additional outside of company clarinet testers, located close to the production facility (during August 2018). They have also a good ability to play the instruments and they have training in the inspection process. They have more than 20 years' experience as players in addition to more than 10 years' experience as play testers; and c) by the ten professional players from university band and orchestra at Purdue University (during September - October 2018). Half of them were advances and half intermediate players. Third group of survey participants were student volunteers from university marching bands and orchestra. They responded on group e-mail call and came to participate in this study. This group of participants could be viewed as future decision-makers (consumers) on the clarinet market. The participants' responses and comments towards potential utilization of U.S. hardwoods for the production of clarinets were recorded and evaluated.

3.3.5.3 Data Analysis and Statistical Tests

The analysis included initial descriptive statistics, in order to compare the average ratings for the different statements. In addition, the ratings were crossed for the different demographic characteristics obtained in the first section of the questionnaire, in order to investigate possible explanatory variables. The variables considered were age, gender, level of professionalism playing clarinet and other musical instrument.

Simple descriptive statistics (Median, Mode, Min. Max and Variance) were calculated and documented for pre-determined evaluation categories namely, Appearance/Color, Touch/Feel, Tone and Quality. Chi-Squared (χ^2) tests (Ott and Longnecker, 2015) were also carried out to compare survey results across wood species and respondent types. Because of non-parametric nature of our data, Kruskal-Wallis Test was used. When p-value was smaller than 0.05, than null hypothesis was rejected. Tukey multiple comparisons tests (Ott and Longnecker, 2015) were carried out to evaluate potential of each clarinet type to replace commonly accepted industrial models namely, Granedilla and ABS Plastic. All tests were carried out at the significance level of

95%. All methods were performed by using the statistical packages available in STATA 15 software (Stata Corp, 2017, College Station, Texas, USA).

Table 3.1 *Physical and mechanical properties of selected wood species (AHEC 2017)*

Wood Species	**SG** (12% MC)	**Average Volumetric Shrinkage** (green to 6% MC),	**MOR** MPa	**MOE** MPa	**Compression Strength** (parallel to grain) MPa	**Hardness** (N)
Cherry	0.50	9.2%	84.809	10,274	49.023	4,226
Maple	0.63	11.9%	108.941	12,618	53.988	6,450
Walnut	0.55	10.2%	100.677	11,584	52.264	4,492
Yellow-poplar	0.42	9.8%	69.640	10,894	38.198	2,402
Grenadilla	1.27	7.7%	213.60	17,950	72.900	1,632

Table 3.2 *Working properties of selected wood species*

Operations	**Maple, hard**	**Walnut, black**	**Cherry, black**	**Yellow-poplar**
Sawing	Excellent	Good	Good	Good
Planing	Good	Excellent	Excellent	Excellent
Drilling	Good	Good	Excellent	Good
Boring	Excellent	Good	Excellent	Good
Turning	Excellent	Excellent	Excellent	Good
Carving	Good	Good	Excellent	Good
Molding	Good	Excellent	Excellent	Excellent
Nailing	Fair	Good	Good	Good
Screwing	Fair	Good	Good	Good
Gluing	Good	Good	Good	Good
Finishing	Excellent	Excellent	Excellent	Excellent

Table 3.3 *Geometry and numbers of wooden specimens prepared and numbers of instruments produced*

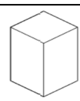
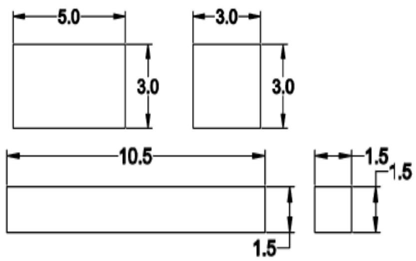
Wood Species & Treatment	**Numbers of Blanks**		**Numbers of Rough Parts**		**Numbers of Finished Parts**		**Numbers of Clarinets Produced**
Part Geometry							
Maple *(Treated)*	2	4	2	4	2	4	2
Maple *(Treated & Dye)*	1	2	1	2	1	2	1
Maple *(Untreated)*	2	4	2	4	2	4	1
Walnut *(Treated)*	2	4	2	4	2	4	0
Walnut *(Untreated)*	2	4	2	4	2	4	2
Cherry *(Treated)*	2	4	2	4	2	4	1
Cherry *(Untreated)*	2	4	2	4	2	4	0
Yellow-poplar *(Treated)*	1	2	1	2	1	2	1
Yellow-poplar *(Treated & Dye)*	1	2	1	2	1	2	1
Yellow-poplar *(Untreated)*	2	4	2	4	2	4	0

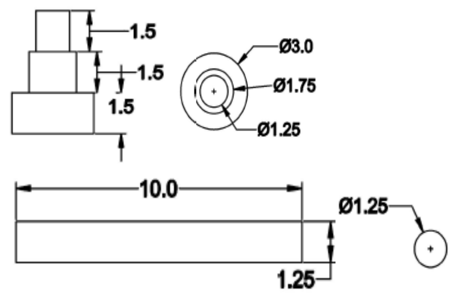
Table 3.4 *Assessment of workability by producer*

(on the scale 1 to 5; 5 being the best)

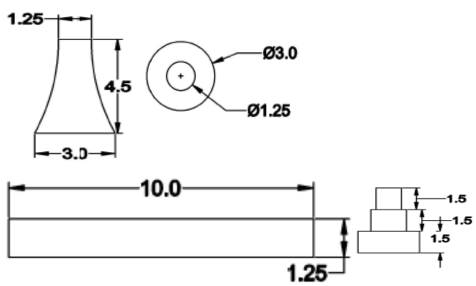
Workability	**None Treated**	**Treated**
Maple	2.5	4.5
Walnut	1	2
Y-poplar	2	2
Y-poplar (T&D)	2	2
Cherry	1	2



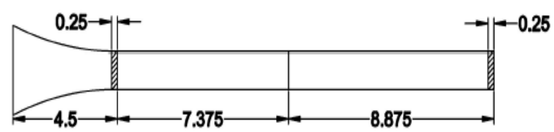
(a)



(b)



(c)



(d)

Figure 3.1 *Geometry of wooden components needed for production of clarinet: a) rectangular blocks; b) roughed-out shapes; c) finished components – smooth, round, hollow cylinder and bell; d) final clarinet assembly from wood components*

Figure 3.2 *Rectangular blocks of wooden components*

Figure 3.3 *Roughed-cut cylinder and bell samples of Hard Maple, Black Walnut, Black Cherry and Yellow Poplar*

(a) (b) (c) (d)

Figure 3.4 *Specimens prepared for shipment to producer: (a) Hard Maple, (b) Black Walnut, (c) Black Cherry, and (d) Yellow Poplar, all untreated wood samples*

Figure 3.5 *MMA treatment process: (a) cactus juice; (b) glass vacuum desiccator; (c) plastic vacuum desiccator filled with cactus juice; (d) baking specimens in the oven (e) treated bells wrapped in aluminum foil; (f) treated cylinders and bells*

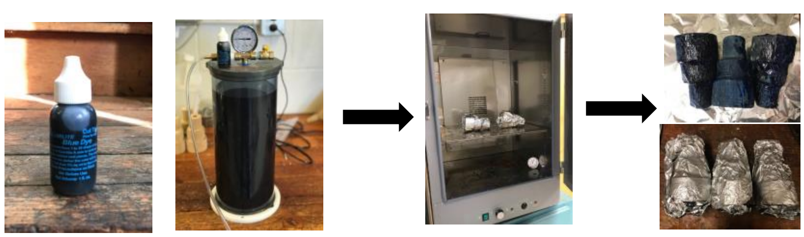


Figure 3.6 *(a) blue dyes; b) plastic vacuum desiccator filled with cactus juice and dye; c) baking specimens in the oven; d) treated and died specimens*

CHAPTER 4. RESULTS

4.1 Outcomes of Manufacturing

Original plan was to produce four instruments of each selected wood species, two natural and two treated, plus two control instruments from Grenadilla and ABS plastic. However, some components did not pass the quality control by producer and were lost at the various stages of manufacturing process. Only components suitable for further production were kept. This loss of specimens is documented in Table 3.3. In total, nine clarinets from four US hardwood species with three different treatments were produced.

Instrument descriptions: Instrument 1 - Yellow-poplar (treated); Instrument 2 - Maple (treated & dyed); Instrument 3 - Maple (treated); Instrument 4 - Maple (treated); Instrument 5 - Cherry (treated); Instrument 6 - Walnut (untreated); Instrument 7 - Walnut (untreated); Instrument 8 - Maple (untreated); Instrument 9 - Yellow-poplar (treated & dyed); Instrument 10 - Grenadilla; and Instrument 11 - ABS plastic. Nine instruments, plus two controls (Grenadilla and ABS plastic) were subjected to consumer perception survey.

4.2 Survey Results

A total of 27 consumer perception surveys were conducted with professional clarinet testers and players. From those, two surveys were conducted by producer with in house professional clarinets testers (internal testers) and fifteen surveys were conducted with additional testers outside the company (external testers). Ten remaining surveys were conducted by the investigator, at the WRL, Purdue University, with volunteer players from university marching band and orchestra.

Responds of first and second group, clarinet testers, are very important because they are considered to be highly trained and experienced experts in the field of clarinet production. Their evaluation will directly influence how likely material substitution will work for the future clarinet market. The results revealed various interesting facets of the participant’ views regarding material used for clarinet production. Of particular interest is the participants' positive attitude towards utilization of sustainable U.S. hardwoods as a substitution for tropical endangers wood species.

4.2.1 Social Demographic Information

Most participants (63%) were professional clarinet testers. Remaining (37%) were clarinet players. More than one-third (37%) of survey participants were male and rest of them were females. Survey participants were divided into two age groups: older than 21 and younger than 21 years, where 63% of the respondents were older and 27% were younger than 21 years. The level of respondent's professionalism was divided into three groups: advanced (20 participants), intermediate (7 participants), and beginners (0 participants). All tested subjects had prior experience playing clarinet. Among 27 participants, 7 could play also other instruments - advanced level, 12 of them could play other instruments - intermediate level, 4 of them could play other instruments - beginner level, and 4 of them couldn't play instruments other than clarinets.

4.2.2 Participants' Choice and Attitudes towards Clarinets Made of U.S. Hardwoods

During the testing process, 11 clarinets were subjected for testing by each survey participant. As described before, nine clarinets were made of U.S. hardwood species (Maple, Walnut, Cherry and Yellow-poplar, and their treatments) and 2 clarinets were traditional (Grenadilla and ABS plastic). Figure 4.1 a) shows all tested clarinets during the surveying process. Figure 4.1 b) shows in details Maple, Walnut, Yellow-poplar and Cherry clarinets.

The participants were asked to play each instrument one by one and assigned grade 1 to 5 (5 as the best). Participants graded each clarinet from four different aspects: Appearance/Color, Touch/Feel, Tone, and Quality. They also added comments to each clarinet after playing.

Results for appearance/color shows: the most favored clarinet was one made of Walnut (untreated); then Maple (treated and dyed). The least favored clarinet was Yellow-poplar (treated), not considering two controls. Table 4.1 shows the mode, median, max, min and variance of appearance/color data. Figure 4.2 shows the perception of survey participants on appearance / color. For benchmarking analysis, the highest column for Grenadilla is score 5, and score 3 for ABS plastic. Thus, none of hardwood species could be comparable with Grenadilla for the aspect of appearance/color, while Maple (treated), Maple (treated & dyed), Walnut (untreated) and Cherry (treated) could all be comparable with ABS plastic clarinet.

Results for touch/feel aspect shows: the most favored clarinet was one made of Maple (treated) and the least favored clarinets were Maple (untreated) and Yellow-poplar (treated), not considering two controls. Considering control Grenadilla and ABS plastic. Table 4.2 shows the mode, median, max, min and variance of touch/feel data. Figure 4.3 shows the perception of survey participants on touch/feel. The highest column for Grenadilla and ABS plastic are both score 4. In the graph, only Maple (treated& dyed) can be comparable with Grenadilla and ABS plastic clarinets.

Results from tone aspect shows: the most favored clarinet was Maple (treated) and the least favored clarinets were Maple (untreated) and Yellow-poplar (treated), not considering two controls. Considering controls Grenadilla and ABS plastic, Table 4.3 shows the mode, median, max, min and variance of tone data. Figure 4.4 shows the perception of survey participants on tone/sound. The highest column for Grenadilla is score 3, and score 5 for ABS plastic. In the graph, Maple (treated & dyed) could be comparable with Grenadilla, and none of the alternative hardwood species could be comparable with ABS plastic.

Results from quality aspect shows: the most favored clarinet was Maple (treated) and the least favored clarinet was Yellow-poplar (treated), except from two control clarinets. Considering controls Grenadilla and ABS plastic, Table 4.4 shows the mode, median, max, min and variance for quality aspect data. Figure 4.5 shows the perception of survey participants on quality for all wood species. The highest column for Grenadilla is score 5 and for ABS plastic is score 4. In the graph, none of the wood species could be comparable with Grenadilla, while Maple (treated & dyed) could be comparable with ABS plastic.

Respond to "Would you purchase this clarinet?" (yes/maybe/no) was: Maple (treated) is the wood species which participants would consider to purchase after the testing. While none of the participants would purchase clarinets made of Yellow-poplar (treated), Yellow-poplar (treated & dyed) and (Maple untreated). This respond does not correlate well with positive oral comments which we received during testing on blue dye treatment. Table 4.5 and Figure 4.6 show the quantitative results for the interests on purchasing clarinets.

4.2.3 Participants' Comments towards Clarinets Made of U.S. Hardwood Species

Comments were collected from each participant for each clarinet. Comments were organized and analyzed according to the instrument and the participant's group, which tested the clarinet: a) in-house testers (2); b) general testers (15) and c) players (10). Then they were organized by the wood species and if comment had positive or negative value. In summary, just about all comments were positive for Grenadilla. For maple clarinets, half of participant's comments were positive for both, testers and players participants. For walnut clarinet, about 35% of comments were positive and 65% negatives. Instruments made of cherry received only few positive comments and instruments made of yellow poplar did not receive any positive comments. In general, participants were very open to the material substitution, but they were not willing to sacrifice the instrument quality. All comments, as they were received, are located in Appendix B.

4.3 Statistical Analysis

The goal was to benchmark different clarinets made of different wood species. Based on statistical analysis, none of the species could be used as a direct substitute for Grenadilla. However, a couple of species are comparable to ABS plastic.

4.3.1 Chi-Square Test Results

Chi-square tests were conducted to evaluate significant differences among nine species and two traditional materials in terms of appearance, tone/sound, touch/feel, and quality. As can be observed in Table 4.6, 4.8 and 4.9, there are significant differences between wood species in terms of appearance, tone/sound and quality with p-values of 0.001, <0.001 and <0.001 at the

95% confidence level, respectively. However, no significant difference was detected for different species in terms of touch/feel as shown in Table 4.7. Touch/Feel comparisons had a p-value of 0.114, which failed to reject the null hypothesis. Moreover, as can be observed in Table 4.10, 4.11, 4.12 and 4.13, there is significant difference between consumer types in terms of appearance, touch/feel, tone/sound, and quality with P-values of <0.001, 0.021, 0.043 and 0.013 at 95% confidence level, respectively. Based on Chi-Square Analysis, it could be concluded that both perception of consumers in terms of appearance, tone/sound, and quality varies depending on species. However, it does not significantly differ in terms of touch/feel. Furthermore, appearance, touch/feel, tone/sound, and quality perception significantly differ across three types of consumers at the 95% confidence level. For detailed chi-square tests results could be viewed in Appendix C.

4.3.2 Kruskal-Wallis Test Results

The survey data was Likert-Type data, and the sample size was relatively small. Thus, to ensure reliability of statistical outcomes, Kruskal-Wallis non-parametric test was conducted. This test was tasked to test Null hypothesis: All medians are equal and Alternative Hypothesis: At least one median is different. Based on analysis results, statistical difference was detected for 11 different clarinet types with p-values of <0.001 for all dependent variables namely, appearance, touch/feel, tone/sound and quality. Since p-value for four different dependent variables were all smaller than 0.05, null hypothesis was rejected. At 95% confidence, Clarinet type is a significant variable for clarinet appearance, touch/feel, tone/sound, and quality. Consumer type is also significant at the same confidence level in terms of perception of appearance and touch/feel but not significant for tone/sound and quality. P-values for appearance and touch/feel were <0.001 and 0.034, respectively. On the other hand, p-values for tone/sound and quality were 0.240 and 0.089, respectively. As all above could be observed in Table 4.14 and detailed Kruskal-Wallis test results are included in Appendix C.

4.3.3 Tukey Test Results

Tukey tests were evaluated in terms of pairwise comparisons. Appearance/Color, Touch/Feel, Tone/Sound and Quality aspects of each clarinet was individually compared against those of Grenadilla and ABS plastic to detect potential of each hardwood species to be a substition for these traditional materials. As can be seen in Table 4.15, at 95% confidence level, in terms of Appearance, Maple (treated) with a p-value of 0.430, Maple (treated & dyed) with a p-value of 0.994 could be a potential substitution for plastic material. Maple (treated) with a p-value of 0.232 of the hardwood species was comparable to Grenadilla at the specified confidence level for this aspect.

Within the scope of Touch/Feel aspect, at the 95% confidence level, comparisons of Maple (treated & dyed), Maple (treated), Cherry (treated), Yellow-poplar (treated & dyed) and Walnut (untreated), with ABS plastic, failed to reject Null Hypothesis with p-values of 0.973, 0.997, 0.752, 0.334 and 0.510, respectively. On the other hand, Maple (treated), Maple (treated & dyed), and Walnut (untreated) failed to reject null hypothesis when compared against Grenadilla in the means of Touch/Feel with p-values of 0.871, 0.244 and 0.067.

As given in the same table, Maple (treated & dyed), and Maple (treated) had insignificant p-values, 0.968 and 1.000 when compared against ABS plastic material in terms of Tone/Sound. In the context of the same aspect, Maple (treated & dyed) also had insignificant p-value, 0.370, when checked against Grenadilla.

Last aspect compared was Quality. Maple (treated & dyed) and Maple (treated) were once again the species whose comparisons against ABS plastic failed to reject Null Hypothesis with p-values of 0.997 and 1.000. Maple (treated & dyed) and Maple (treated) with p-values of 0.193 and 0.486 failed to reject Null Hypothesis when compared with Grenadilla, as can be observed in Table 4.16. Detailed Tukey results are in Appendix C.

4.3.4 Mann-Whitney Test Results

Within Mann-Whitney tests, the Null hypothesis: H_0: $\eta_1 - \eta_2 = 0$; and alternative hypothesis: H_1: $\eta_1 - \eta_2 \neq 0$ were evaluated in terms of pairwise comparisons. Appearance, Touch/Feel, Tone/Sound and Quality aspects of each clarinet was individually compared against those of Grenadilla and ABS plastic to detect potential of each hardwood species to be a substition for these traditional materials. As can be seen in Table 4.16, at 95% confidence level, in terms of Appearance, Maple (treated) with a p-value of 0.235, Maple (treated & dyed) with a p-value of 0.557, Cherry (treated) with a p-value of 0.554, Walnut (untreated) with p-values of 0.204 and 0.658, as well as Yellow Poplar (treated & dyed) with a p-value of 0.248 could be a potential substitution for ABS plastic material. None of the hardwood species were comparable to Grenadilla at the specified confidence level for this aspect.

Within the scope of Touch/Feel aspect, at the 95% confidence level, comparisons of Maple (treated & dyed), Maple (treated), Cherry (treated) and Walnut (untreated) with ABS plastic failed to reject Null Hypothesis with p-values of 0.198, 0.629, 0.071 and 0.072, respectively. On the other hand, only Maple (treated) failed to reject null hypothesis when compared against Grenadilla in the means of Touch/Feel.

As given in the same table, Maple (treated & dyed) and Maple (treated) had insignificant p-values, 0.297 and 0.481 when compared against ABS plastic material in terms of Tone/Sound. In the context of the same aspect, Maple (treated) also had insignificant p-value, 0.069, when checked against Grenadilla.

Last aspect compared was Quality and Maple (treated & dyed) and Maple (treated) were once again the species whose comparisons against ABS plastic failed to reject Null Hypothesis. Comparison of none of the hardwood species with Grenadilla had insignifant p-values as can be observed in Table 4.16.

Table 4.1 *Appearance / Color*

	MODE	**MEDIAN**	**MAX**	**MIN**	**VAR**
YP *(Treated)*	2	2	4	1	1.0
Maple *(Treated&Dye)*	4	4	5	1	1.8
Maple *(Treated)*	3	3	5	1	1.4
Maple *(Treated)*	3	3	5	1	1.1
Cherry *(Treated)*	4	4	5	1	1.7
Walnut *(Untreated)*	3	3	5	1	1.4
Walnut *(Untreated)*	4	4	5	2	0.7
Maple *(Untreated)*	2	3	5	1	2.1
YP *(Treated&Dye)*	4	4	5	1	1.5
Grenadilla	5	5	5	3	0.6
Plastic (ABS)	3	4	5	3	0.7

Table 4.2 *Touch / Feel*

	MODE	MEDIAN	MAX	MIN	VAR
YP *(Treated)*	3	3	5	1	1.0
Maple *(Treated&Dye)*	3	3	5	1	1.3
Maple *(Treated)*	3	3	5	2	1.1
Maple *(Treated)*	3	4	5	2	0.9
Cherry *(Treated)*	3	3	5	1	1.0
Walnut *(Untreated)*	3	3	5	1	1.2
Walnut *(Untreated)*	3	3	5	2	1.5
Maple *(Untreated)*	3	3	4	1	0.8
YP *(Treated&Dye)*	5	3	5	1	1.0
Grenadilla	5	4	5	3	0.7
Plastic (ABS)	3	4	5	1	1.2

Table 4.3 *Tone*

	MODE	**MEDIAN**	**MAX**	**MIN**	**VAR**
YP *(Treated)*	1	1	3	1	0.4
Maple *(Treated&Dye)*	4	4	5	2	1.0
Maple *(Treated)*	3	3	5	2	1.0
Maple *(Treated)*	4	4	5	1	1.5
Cherry *(Treated)*	1	1	5	1	0.9
Walnut *(Untreated)*	2	2	5	1	1.2
Walnut *(Untreated)*	3	3	5	1	1.0
Maple *(Untreated)*	1	1	3	1	0.4
YP *(Treated&Dye)*	1	2	3	1	0.4
Grenadilla	4	4	5	1	1.2
Plastic (ABS)	4	4	5	2	0.7

Table 4.4 *Quality*

	MODE	**MEDIAN**	**MAX**	**MIN**	**VAR**
YP *(Treated)*	1	1	2	1	0.3
Maple *(Treated&Dye)*	4	4	5	1	1.0
Maple *(Treated)*	3	3	5	2	1.0
Maple *(Treated)*	3	3	5	1	1.4
Cherry *(Treated)*	1	2	5	1	0.9
Walnut *(Untreated)*	3	3	4	1	0.7
Walnut *(Untreated)*	3	3	5	1	0.9
Maple *(Untreated)*	2	2	4	1	0.7
YP *(Treated&Dye)*	2	2	3	1	0.5
Grenadilla	4	4	5	1	1.1
Plastic (ABS)	4	4	5	2	0.8

Table 4.5 *Purchase aspect for testing clarinets*

Purchase	**Yes**	**Maybe**	**No**	**No Response**
YP *(Treated)*	0	0	27	0
Maple *(Treat&Dye)*	10	9	6	2
Maple *(Treated)*	11	7	6	3
Maple *(Treated)*	7	6	11	3
Cherry *(Treated)*	2	0	23	2
Walnut *(Untreated)*	2	8	13	4
Walnut *(Untreated)*	3	7	12	5
Maple *(Untreated)*	0	1	22	4
YP *(Treated&Dye)*	0	1	22	4
Grenadilla	11	6	1	9
Plastic (ABS)	6	5	5	11

Chi-Square Test

Table 4.6 *Chi-square test for different wood species in terms of appearance*

Appearance						
Type	1	2	3	4	5	Total
Cherry (Treated)	3	2	6	7	6	24
Grenadilla	0	0	3	4	11	18
Maple (Treated & Dyed)	3	2	5	8	7	25
Maple (Treated)	2	6	7	6	3	24
Maple (Untreated)	5	6	3	6	4	24
Maple II (Treated)	1	2	10	6	5	24
Plastic (ABS)	0	0	6	5	5	16
Walnut (Untreated)	3	0	8	8	3	22
Walnut II (Untreated)	0	1	8	9	5	23
Yellow-poplar (Treated & Dyed)	4	9	7	4	0	24
Yellow-poplar (Treated & Dyed)	3	1	7	8	4	23
Total	24	29	70	71	53	247
Pearson $chi^2(40) = 73.5486$	Pr=0.001					

According to Table 4.6, P-value=0.001<0.05, At 95% confidence, there is a significant difference between clarinet types in terms of appearance.

Table 4.7 *Chi-square test for different wood species in terms of touch/feel*

Touch/Feel						
Type	1	2	3	4	5	Total
Cherry (Treated)	1	4	10	7	2	24
Grenadilla	0	0	4	6	8	18
Maple (Treated & Dyed)	1	5	7	7	5	25
Maple (Treated)	0	4	10	4	6	24
Maple (Untreated)	2	7	10	5	0	24
Maple II (Treated)	0	2	9	7	6	24
Plastic (ABS)	1	0	5	5	5	16
Walnut (Untreated)	1	6	9	4	4	23
Walnut II (Untreated)	0	6	10	3	4	23
Yellow-poplar (Treated & Dyed)	3	4	12	4	1	24
Yellow-poplar (Treated & Dyed)	2	4	10	6	1	23
Total	11	42	96	58	41	248
Pearson $chi^2(40)= 50.9976$	Pr=0.114					

According to Table 4.7, P-value=0.114<0.05, At 95% confidence, there is not a significant difference between clarinet types in terms of touch/feel.

Table 4.8 *Chi-square test for different wood species in terms of tone/sound*

Tone/Sound						
Type	1	2	3	4	5	Total
Cherry (Treated)	18	4	2	0	1	25
Grenadilla	1	1	1	8	7	18
Maple (Treated & Dyed)	0	7	4	12	2	25
Maple (Treated)	0	3	10	6	5	24
Maple (Untreated)	13	9	2	0	0	24
Maple II (Treated)	2	4	6	8	4	24
Plastic (ABS)	0	1	5	7	3	16
Walnut (Untreated)	3	9	6	4	1	23
Walnut II (Untreated)	2	8	9	3	1	23
Yellow-poplar (Treated & Dyed)	16	6	2	0	0	24
Yellow-poplar (Treated & Dyed)	11	10	2	0	0	23
Total	66	62	49	48	24	249
Pearson $chi^2(40)= 182.7363$	Pr<0.001					

According to Table 4.8, P-value<0.001<0.05, At 95% confidence, there is a significant difference between clarinet types in terms of tone/sound.

Table 4.9 *Chi-square test for different wood species in terms of overall quality*

Quality						
Type	1	2	3	4	5	Total
Cherry (Treated)	10	10	2	0	1	23
Grenadilla	1	0	3	7	7	18
Maple (Treated & Dyed)	1	5	6	12	1	25
Maple (Treated)	0	5	8	7	4	24
Maple (Untreated)	9	10	4	1	0	24
Maple II (Treated)	2	3	7	7	4	23
Plastic (ABS)	0	2	5	7	2	16
Walnut (Untreated)	2	8	10	3	0	23
Walnut II (Untreated)	2	5	11	4	1	23
Yellow-poplar (Treated & Dyed)	13	11	0	0	0	24
Yellow-poplar (Treated & Dyed)	7	11	3	0	0	21
Total	47	70	59	48	20	244
Pearson $chi^2(40) = 182.7363$	$Pr<0.001$					

According to Table 4.9, P-value<0.001<0.05, At 95% confidence, there is a significant difference between clarinet types in terms of quality.

Table 4.10 *Chi-square test for consumer types in terms of appearance*

Appearance						
Consumer Type	1	2	3	4	5	Total
Players	1	10	25	47	25	108
Internal Testers	10	1	9	0	2	22
External Testers	13	18	36	24	26	117
Total	24	29	70	71	53	247
Pearson $chi^2(40)$= 62.1246	Pr<0.001					

According to Table 4.10, P-value<0.001<0.05, at 95% confidence, there is a significant difference between consumer types in terms of appearance.

Table 4.11 *Chi-square test for consumer types in terms of touch/feel*

Touch/Feel						
Consumer Type	1	2	3	4	5	Total
Players	2	14	41	34	18	109
Internal Testers	2	3	14	2	1	22
External Testers	7	25	41	22	22	117
Total	11	42	96	58	41	248
Pearson $chi^2(40)= 18.0064$	Pr=0.021					

According to Table 4.11, P-value=0.021<0.05, at 95% confidence, there is a significant difference between consumer types in terms of touch/feel.

Table 4.12 *Chi-square test for consumer types in terms of tone/sound*

Tone/Sound						
Consumer Type	1	2	3	4	5	Total
Players	19	33	24	25	8	109
Internal Testers	8	4	7	2	1	22
External Testers	39	25	18	21	15	118
Total	66	62	49	48	24	249
Pearson $chi^2(40)= 15.9631$	Pr=0.043					

According to Table 4.12, P-value=0.043<0.05, at 95% confidence, there is a significant difference between consumer types in terms of tone/sound.

Table 4.13 *Chi-square test for consumer types in terms of quality*

Quality						
Consumer Type	1	2	3	4	5	Total
Players	11	34	32	24	8	109
Internal Testers	8	3	8	2	1	22
External Testers	28	33	19	22	11	113
Total	47	70	59	48	20	244
Pearson $chi^2(40)$= 19.3061	Pr=0.013					

According to Table 4.13, P-value=0.013<0.05, at 95% confidence, there is a significant difference between consumer types in terms of quality.

Kruskal-Wallis Test

Table 4.14 *Kruskal-Wallis test*

Null hypothesis	H_0: All medians are equal		
Alternative hypothesis	H_1: At least one median is different		
Method	DF	H-Value	P-Value
Clarinet Type on Appearance			
Not adjusted for ties	10	36.76	<0.001
Adjusted for ties	10	36.76	<0.001
Clarinet Type on Touch/Feel			
Not adjusted for ties	10	31.92	<0.001
Adjusted for ties	10	34.70	<0.001
Clarinet Type on Tone/Sound			
Not adjusted for ties	10	125.31	<0.001
Adjusted for ties	10	131.86	<0.001
Clarinet Type on Quality			
Not adjusted for ties	10	107.80	<0.001
Adjusted for ties	10	113.84	<0.001
Consumer Type on Appearance			
Not adjusted for ties	2	25.94	<0.001
Adjusted for ties	2	27.56	<0.001
Consumer Type on Quality			
Not adjusted for ties	2	4.85	0.089
Adjusted for ties	2	5.12	0.077
Consumer Type on Tone/Sound			
Not adjusted for ties	2	2.85	0.240
Adjusted for ties	2	3.00	0.223
Consumer Type on Touch/Feel			
Not adjusted for ties	2	6.75	0.034
Adjusted for ties	2	7.34	0.026

Table 4.15 *Tukey Test for potential substitution of wood species*

Tukey	Plastic	P-value	Grenadilla	P-value
Appearance	**Maple (T & Dyed)**	**0.994**	**Maple (Treated)**	**0.232**
	Maple (Treated)	**0.430**		
Touch/Feel	Yellow-poplar (Treated)	0.103	**Maple (T & Dyed)**	**0.244**
	Maple (T & Dyed)	**0.973**	**Maple (Treated)**	**0.871**
	Maple (Treated)	**0.997**	Walnut (Untreated)	0.067
	Cherry (Treated)	0.752		
	Walnut (Untreated)	0.510		
	Yellow-poplar (T & Dyed)	0.334		
Tone/Sound	**Maple (T & Dyed)**	**0.968**	**Maple (T & Dyed)**	**0.370**
	Maple (Treated)	**1.000**		
Quality	**Maple (T & Dyed)**	**0.997**	**Maple (T & Dyed)**	**0.193**
	Maple (Treated)	**1.00**	**Maple (Treated)**	**0.486**
	Walnut (Untreated)	0.060		
Conclusive Choice	**Maple (Treated)**		**Maple (Treated)**	

Table 4.16 *Mann-Whitney test for potential substitution wood species*

Mann-Whitney	Plastic	P-value	Grenadilla	P-value
Appearance	**Maple (T & Dyed)**	**0.557**		
	Maple (Treated)	**0.235**		
	Cherry (Treated)	0.554		
	Walnut (Untreated)	0.658		
	Y-poplar (T & Dyed)	0.248		
Touch/Feel	**Maple (T & Dyed)**	**0.198**	**Maple (Treated)**	**0.101**
	Maple (Treated)	**0.629**		
	Cherry (Treated)	0.071		
	Walnut (Untreated)	0.072		
Tone/Sound	**Maple (T & Dyed)**	**0.297**	**Maple (Treated)**	**0.069**
	Maple (Treated)	**0.481**		
Quality	**Maple (T & Dyed)**	**0.297**		
	Maple (Treated)	**0.481**		
Potential Substitution	**Maple (T & Dyed)**		**Maple (Treated)**	
	Maple (Treated)			

a)

b)

Figure 4.1 a) *Clarinets submitted to the survey process;* b) *Detailed clarinets made of maple, walnut, yellow-poplar and cherry wood*

Figure 4.1 continued

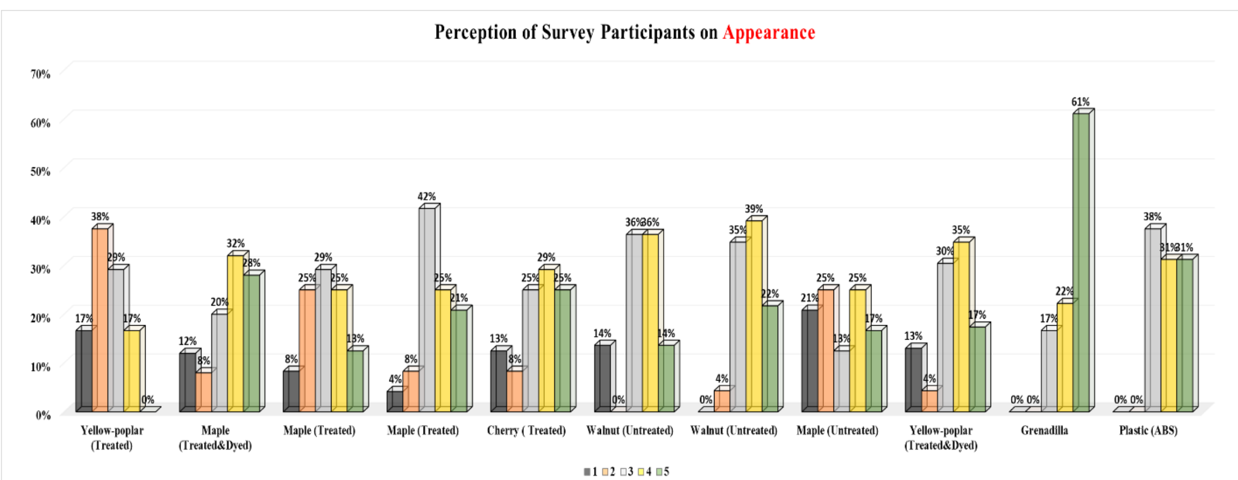


Figure 4.2 *Perception of survey participants on Appearance / Color*

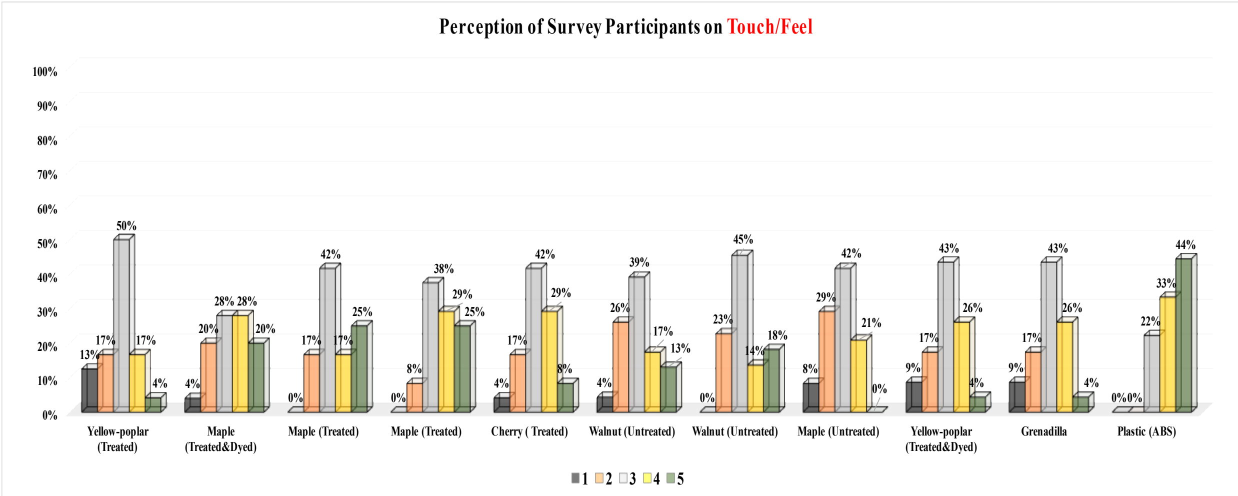


Figure 4.3 *Perception of survey participants on Touch / Feel*

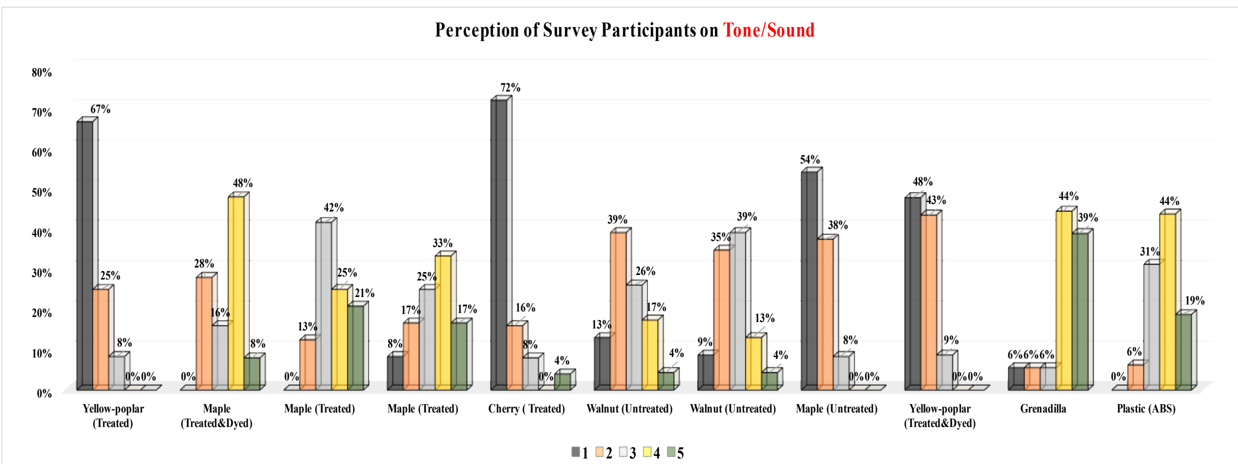


Figure 4.4 *Perception of survey participants on Tone*

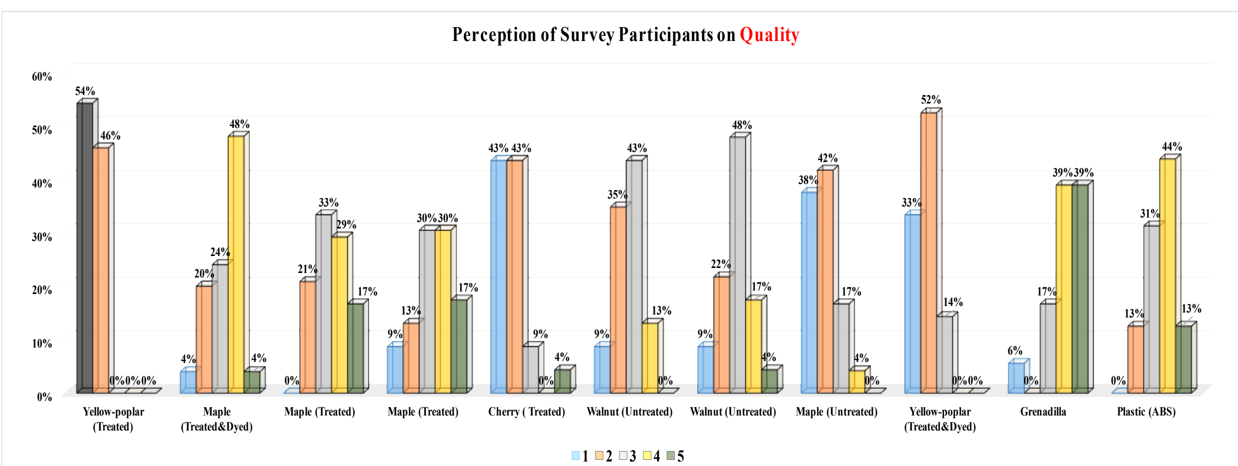


Figure 4.5 *Perception of survey participants on Quality*

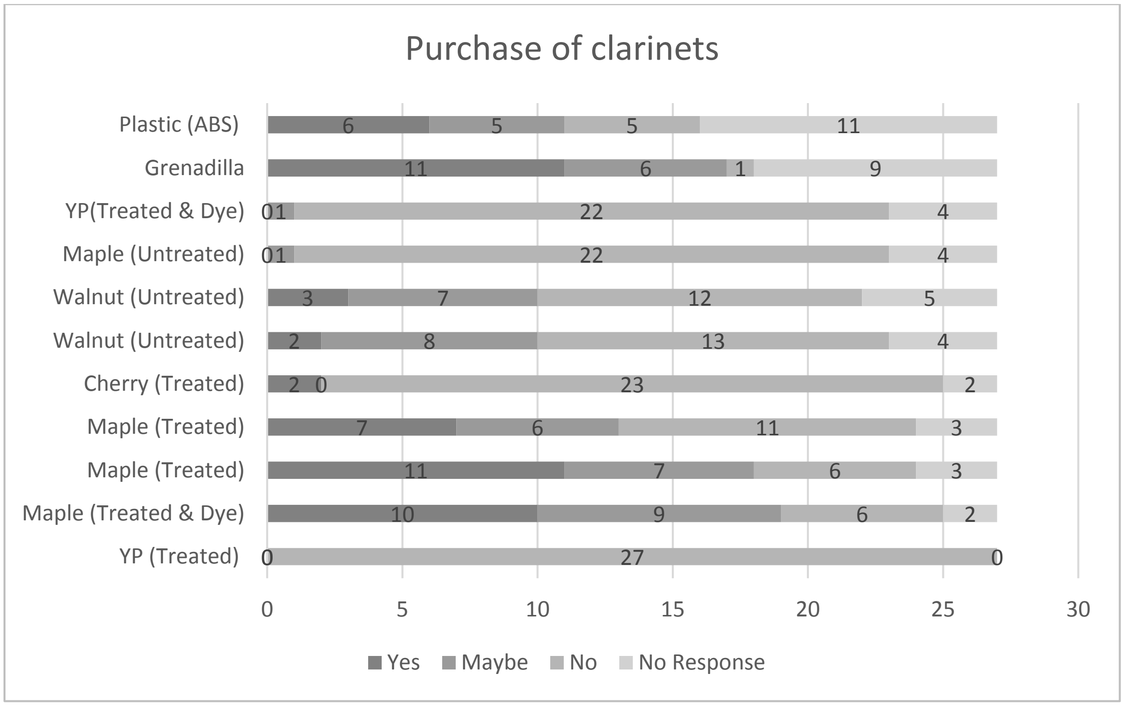


Figure 4.6 *Interest for purchase of clarinets*

CHAPTER 5. DISCUSSIONS

The main objective of this study was to assess feasibility of substituting tropical wood species with the U.S. hardwood species for the production of clarinets. Outcomes of literature review and discussions with forest products industry professionals and clarinet producer lead to the consideration to test four U.S. hardwood species for potential production of clarinets. The main goal is to find acceptable substitution for threatened tropical wood species Grenadilla. Properties of U.S. hardwood species are in general much lower values (about half) than Grenadilla but aesthetic value and workability of these species are relevant. Good workability is the most important material attribute from the perspective or producer. To improve wood properties, several treatments were investigated. Cactus juice treatment was selected and tested as a potential treatment for material improvement because of its feasibility (mainly time and equipment cost limitations). Other densification methods could be addressed and tested by future research. Workability of treated and untreated material was assessed and 9 instruments were produced from fours U.S. hardwood species. These were benchmarked with traditional instruments made of Grenadilla and ABS plastic. Consumer acceptance of clarinets made of U.S. hardwoods was assessed by surveying, where professional clarinet testers and players observed, played, ranked instruments, and benchmark them with traditional instruments.

5.1 Participants' Feedback on Tested Clarinets

Feedback from testers: Seventeen experienced clarinet testers and ten experienced players evaluated eleven different instruments. In general, this group likes traditional instruments with no change. A majority of players expressed a deep interest in the study, they volunteered to perform evaluations and were opened to explore potential change in material used for clarinet production. Possibility to use alternative wood species for production of clarinets was very intriguing to them. They were fine with materials substitution, but were looking for very comparable performance quality as traditional instruments. Many participants expressed interest in blue dye treatment and color change in oral conversation but limited comments appeared in survey.

Feedback from producer: Producer feels that Maple and marginally Walnut have potential as species for substitution. However, they understand that further study and more time is needed for process improvement and additional machining tuning. Material processing, such as speed of wood turning and hole boring, for different shapes would be one possible variable, as well as different wood treatments and finishes. Producer is considering expounding the study. Producer also expressed great interest in blue dye treatment. Treated maple received the highest ratings in all studied categories.

5.2 Limitations of the Study

Firstly, materials properties of selected wood species are not comparable to quality of materials traditionally used. Therefore, material treatments, more specifically treatment with cactus juice, was investigated and explored. Further exploration, evaluation, and benchmarking of physical & mechanical properties of different materials and their treatments could be performed by future studies. Secondly, during the process of machining into final instrument components, we lost many wood components and on the end full clarinet samples from Yellow Poplar (untreated), Cherry (untreated) and Walnut (treated) which could not be produced. Therefore, the clarinet sample sizes from all four wood species, treated and untreated, are not balanced. Thirdly, the sample size of clarinets for testing was very small but in our case, sample size increase would not be feasible. Fourth, design of the survey could be improved (increasing the scale from 5 to 10). Fifth, some survey participants (specifically external testers) did not complete all comments of the survey. There was a time constrain while performing survey with this group. Providing testers with more time and giving them an incentive for completion of the survey would be helpful.

5.3 Future Research

Maple (treated) clarinets showed significate advantage over the other species when compared with clarinets from Grenadilla and ABS plastic. Therefore, further study could be designed for Maple (treated) clarinets production, specifically machining and instrument stability in relation to the moisture content changes.

Walnut (treated) was not fully investigated but based on the limited data, this species also showed promise and it would be interesting to investigate further the option of using treated Walnut. Feasibility of treatment with cactus juice would have to be also addressed. Specifically, performing extended analysis on physical and mechanical properties, as well as cost analysis.

CHAPTER 6. CONCLUSION

The U.S. has an abundance of hardwood resource in a wide variety of species to choose from. It is a non-toxic, low-impact material, which could be of high quality and durability and it is available in great volumes. Industry processing this material can give assurance that their hardwood products come from legal and sustainable sources. The U.S. hardwoods are one of the most environmentally friendly raw materials available to producers of wood products. Illegal sourcing of some tropical wood species is having negative effect on deforestation. Musical industry is affected by environmental regulations and is looking for alternative sources for specific material used for production of their products.

This study was looking for potential substitution for Grenadilla in production of wooden clarinets. Based on the Mann-Whitney test and Tukey Test, we obtained potential hardwood species for production of clarinet. From Tukey results, could be concluded that Maple (treated) was comparable with both, Grenadilla and ABS plastic clarinet, and could be potential wood species for substitution. From Mann-Whitney results could be also concluded that Maple (treated) is the best U.S. hardwood species suitable for clarinet production when compared with ABS plastic. When compared with Grenadilla, Maple (treated) was comparable only in touch/feel and tone/sound aspects. This conclusion is based on results from all four studied aspects (color, touch and feel, performance and overall quality).

All study participants were very open to the idea of using U.S. hardwoods for production of clarinets. Alternative materials for clarinets were easily accepted based on visual appearance but there were many concerns about their performance, which was strongly reflected in evaluator's comments. Treated Maple was selected as the best of all material substitution but in order to obtain stronger confirmation and best of all results, there is still the need for further study, which should address improvements in the area of material processing, treatments, and its dimensional stability. In conclusion, to find substitution for endangered wood species is an urgent and challenging call for producers of musical instruments. This study is just a start to address this issue.

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APPENDIX A. CONSUMER PERCEPTION SURVEY

Demographic Questions:

1. Age: Younger than 21 years ☐ 21 years and older ☐

2. Gender: Female ☐ Male ☐

Musical Experience:

1. Do you play clarinet? Yes ☐ No ☐

If yes, mark your experience level: Beginner ☐ Intermediate ☐ Advanced ☐

2. Do you play other musical instruments? Yes ☐ No ☐

If yes, mark your experience level: Beginner ☐ Intermediate ☐ Advanced ☐

Musical Instrument Number: ☐

Preference Questions:

1. Please, select appropriate level 1-5 for the instrument you are evaluating (5 is the best).

	1	2	3	4	5
Appearance/Color					
Touch/Feel					
Tone/Sound					
Overall Quality					

2. Would you consider purchasing this instrument? Yes ☐ No ☐ Maybe ☐

3. Please, add any comments.

Musical Instrument Number: ☐

Preference Questions:

1. Please, select appropriate level 1-5 for the instrument you are evaluating (5 is the best).

	1	2	3	4	5
Appearance/Color					
Touch/Feel					
Tone/Sound					
Overall Quality					

2. Would you consider purchasing this instrument? Yes ☐ No ☐ Maybe ☐

3. Please, add any comments.

Musical Instrument Number: ☐

Preference Questions:

1. Please, select appropriate level 1-5 for the instrument you are evaluating (5 is the best).

	1	2	3	4	5
Appearance/Color					
Touch/Feel					
Tone/Sound					
Overall Quality					

2. Would you consider purchasing this instrument? Yes ☐ No ☐ Maybe ☐

3. Please, add any comments.

Musical Instrument Number: ☐

Preference Questions:
1. Please, select appropriate level 1-5 for the instrument you are evaluating (5 is the best).

	1	2	3	4	5
Appearance/Color					
Touch/Feel					
Tone/Sound					
Overall Quality					

2. Would you consider purchasing this instrument? Yes ☐ No ☐ Maybe ☐

3. Please, add any comments.

Musical Instrument Number: ☐

Preference Questions:
1. Please, select appropriate level 1-5 for the instrument you are evaluating (5 is the best).

	1	2	3	4	5
Appearance/Color					
Touch/Feel					
Tone/Sound					
Overall Quality					

2. Would you consider purchasing this instrument? Yes ☐ No ☐ Maybe ☐

3. Please, add any comments.

Musical Instrument Number: ☐

Preference Questions:
1. Please, select appropriate level 1-5 for the instrument you are evaluating (5 is the best).

	1	2	3	4	5
Appearance/Color					
Touch/Feel					
Tone/Sound					
Overall Quality					

2. Would you consider purchasing this instrument? Yes ☐ No ☐ Maybe ☐

3. Please, add any comments.

Musical Instrument Number: ☐

Preference Questions:
1. Please, select appropriate level 1-5 for the instrument you are evaluating (5 is the best).

	1	2	3	4	5
Appearance/Color					
Touch/Feel					
Tone/Sound					
Overall Quality					

2. Would you consider purchasing this instrument? Yes ☐ No ☐ Maybe ☐

3. Please, add any comments.

Musical Instrument Number: ☐

Preference Questions:

1. Please, select appropriate level 1-5 for the instrument you are evaluating (5 is the best).

	1	2	3	4	5
Appearance/Color					
Touch/Feel					
Tone/Sound					
Overall Quality					

2. Would you consider purchasing this instrument? Yes ☐ No ☐ Maybe ☐

3. Please, add any comments.

Musical Instrument Number: ☐

Preference Questions:

1. Please, select appropriate level 1-5 for the instrument you are evaluating (5 is the best).

	1	2	3	4	5
Appearance/Color					
Touch/Feel					
Tone/Sound					
Overall Quality					

2. Would you consider purchasing this instrument? Yes ☐ No ☐ Maybe ☐

3. Please, add any comments.

Musical Instrument Number: ☐

Preference Questions:

1. Please, select appropriate level 1-5 for the instrument you are evaluating (5 is the best).

	1	2	3	4	5
Appearance/Color					
Touch/Feel					
Tone/Sound					
Overall Quality					

2. Would you consider purchasing this instrument? Yes ☐ No ☐ Maybe ☐

3. Please, add any comments.

Musical Instrument Number: ☐

Preference Questions:

1. Please, select appropriate level 1-5 for the instrument you are evaluating (5 is the best).

	1	2	3	4	5
Appearance/Color					
Touch/Feel					
Tone/Sound					
Overall Quality					

2. Would you consider purchasing this instrument? Yes ☐ No ☐ Maybe ☐

3. Please, add any comments.

APPENDIX B. PARTICIPANTS' COMMENTS ON INDIVIDUAL INSTRUMENTS

Yellow-poplar (Treated):

Group a (in-house testers)

1. "Like playing a sock";
2. "Couldn't get any sound from this, upper is obviously leaking seriously";

Group b (general testers)

3. "Wood is not sealed. rough finish";
4. "Wood fibers are loose. Unclean look. Pads don't seat well over tone holes. Stuffy tone. Other than open g didn't sound. Upper register is flat";
5. "Maybe a leak?";
6. "Adding fingers=hard to play, inconsistent & tough over break";
7. "Tough to play!";
8. "Tone sound below the break is good but muffled. Past g above the staff is resistant and weak";
9. "More trouble w/this instrument in the upper register";
10. "Clarinet barely works";
11. "Does not play";

Group c (players)

12. "The middle register does sound good, but with octave key, no sound comes out";
13. "Adjustment issue";
14. "Very resistant in playing, not all notes come easily; rough to touch in some places; hard to play high notes";
15. "Couldn't get above middle register";
16. "Issues in upper register; feels really soft not quickly responsive";
17. "No response above the g above the staff";

18. “High notes hard to play, cannot play all notes”;
19. “Can't play all notes (c, b is ok)”;
20. “Keys feel cheap; poor control, neat color; overall manufacturing quality seems poor; poor tone quality through the range; could not get sound on high notes; squeaky sounds cheap”;
21. “Loose stability in upper range, hard to play in upper tone; fuzzy tone”.

Maple (Treated & Dyed):

Group a (in-house testers)

1. “Does not project, loses stability in upper range, fuzzy tone quality”;
2. “Had some issue with getting joints to fit together. Wood may have shrunk since manufactured, body has rough feel to it. Covering issues made playing difficult. Interesting color”;

Group b (general testers)

3. “High 3 is flat. Good clear tone. Throat tones are clear”;
4. “Resistant in odd place”;
5. “Bright tone, resistant over g5”;
6. “Great for beginners?”;
7. “Some notes stuffy and clunky feel, otherwise beautiful resonant sound”;
8. “Altissimo is bright”;
9. “Love the tone of this clarinet”;
10. “Very smooth, perhaps flat”;
11. “Playable but zero projection”;

Group c (players)

12. “All sounds were mostly clear, and the middle register is somewhat flat”;
13. “Rough finger notes, love blue color”;
14. “Note came easier, some rougher than others; not consistent in note quality”;
15. “Good range, good quality; a little resonant in the keys, love the blue”;

16. “Steaking in dye makes it seems like it could be for a kids, but really nice and responsive”;
17. “Large variation in tuning of notes; not consistent”;
18. “Easy to play; good tone”;
19. “Sticky pads. Unfinished area around keys/ could be sanded”;
20. “Great tone, very easy to play; unique color; keys feel well machined are good seal”;
21. “Lose stability in ultrahigh range; fuzzy tone in low range”.

Maple (Treated):

Group a (in-house testers)

1. “Better than 1, 2, 7, but still loses projection in upper register”;
2. “This one played but sound quality was dull. No "ring" to the wood”;

Group b (general testers)

3. “Wood fibers around keys not cleanly cut”;
4. “Altissimo register sounds clear. Throat tones also sound clear. I like this clarinet a lot”;
5. “Easy to play, less overtones on e3, less resistance, little sacrifice in quality”;
6. “Best so far!”;
7. “Love the sound and feel. it responds very well”;
8. “Very rich vibrant sound”;

Group c (players)

9. “Better playability and slightly more projection”;
10. “All sound came out, and middle register sounds fine”;
11. “Favorite so far, beautiful tone”;
12. “Plays sharp; similar range to no.2; more consistent than no.2”;
13. “Upper joint key was too low; quality a little extremely great whole tone”;
14. “Sounds bright like a plastic clarinet”;
15. “Some tuning issues, especially c, d below the staff, sharp”;
16. “Richer/darker sound, intonation not so good”;
17. “I prefer tone of no.2”;

18. “Poor manufacturing quality, good tone high flow, good key action”.

Maple (Treated):

Group a (in-house testers)

1. “This is probably the best of the experimental woods. Still a degree of fuzziness to the tonal quality”;
2. “Joint fit tight. Sounds ok. Question if grain could withstand over time and not crack”;

Group b (general testers)

3. “Tuning is not consistent. Some holes are stuffy. Tone holes are rough cut”;
4. “Throat tone is fuzzy. Middle c is slightly stuffy”;
5. “Feels like normal, not overly easy - good resistance, responsive”;
6. “Good dark tone”;
7. “Very stuffy sound”;
8. “Free blow”;
9. “Love the feel and the tone of this instrument. Responds very well”;
10. “Sound fluctuates too much”;
11. “No presence of sound”;

Group c (players)

12. “The sound in the larger register is very good, middle register seems a bit flat”;
13. “Not as rich tone quality”;
14. “Similar to no.2 no.3; inconsistent between ranges; also resistant”;
15. “Tone quality not as great”;
16. “Liked the grain better, but it was less responsive than no.3 in upper register and had more biting tone”;
17. “High f is flat; poor response is high g, f above right the staff”;
18. “Fuzzy; very responsive”;
19. “Color not as pretty as no.3”;
20. “Some keys feel stiff some lose, manufacturing quality pool. doesn't respond well, gaps between notes”;

21. “Great tone, fuzzy noise in middle range”.

Cherry (Treated):

Group a (in-house testers)

1. “Like a sock”;
2. “Could get no sound form this. Overall very light weight and open grain”;

Group b (general testers)

3. “Tone stuffy as fingers are added. Difficult to speak c5”;
4. “Middle c is stuffy. Tone hole on bottom is chipped. A lot of air is needed to get out left hand upper register notes”;
5. “Maybe leaks?”;
6. “Hard to play over break, muffled sound”;
7. “Something is wrong with lower joint”;
8. “Overall light feeling, muffled, the register crossing is really resistant. Altissimo is weak”;
9. “Very stuffy”;
10. “Instrument was responsive in the lower register but not so much in the upper register”;
11. “Clarinet barely speaks but is a cool rubbery sound”;
12. “Terrible”;

Group c (players)

13. “Sound in the middle register is good, but high notes do not come out well”;
14. “Adjustment issue”;
15. “Notes don't speak; looks nice, but is hard to play; gets a tiny bit better with time”;
16. “Difficult to play”;”
17. Feels soft, slow responsive have to overblow to get any of upper register. Not playable really light”;
18. “No response over middle b”;
19. “Cannot play high notes”;

20. “Bells looks like different color. Lower keys don’t produce notes’;
21. “Quality of manufacture is poor, loose keys, b7c staff notes don't sound, marginal tone quality”;
22. “Can't play after 5 notes, fuzzy noise bad tone”.

Walnut (Untreated):

Group a (in-house testers)

1. “Better than 1, 2, 3, 5, 7, 9”;
2. “This one has an odd sound to it. I am sure the type of wood is the issue. Also bore is very rough”;

Group b (general testers)

3. “Rough cut tone holes. Flat c5, bb5. Much of clarinet is low in pitch”;
4. “Stuffy tone in upper register. Open g has a clear tone”;
5. “Thin and stuffy”;
6. “Better than 3, worse than 4! Still good playing”;
7. “For beginner, not even tone across registers”;
8. “Spread tone, student quality”;
9. “Great feel, but I didn't care for the tone quality. It sounded flat to me”;
10. “A little stuffy”;
11. “Terrible”;

Group c (players)

12. “It had a very rich sound in the low notes, but middle register is slightly flat, high register somewhat hard to play”;
13. “Not as resonant as deep”;
14. “Notes spoke, but some were harder than others, sharp”;
15. “Tuner key is off, made going touch difficult, tone quality decline at extreme range”;
16. “Really flat in upper register. Like how light it is but feels rough”:
17. “Response issues with high notes, tuning issues-left hand notes flat, right hand notes sharp”;

18. “Flat in upper register, upper register sounds sweet”;
19. “Lower keys sometimes play, mostly can't make notes, feels clankier”;
20. “Clicking of keys is annoying, not smooth to touch, hesitant between notes, low notes poor quality at sound”;
21. “Lose stability in high range, can’t play low range, fuzzy noise in middle range”.

Walnut (Untreated):

Group a (in-house testers)

1. “Fuzzy tone quality, loses projection in upper register”;
2. “Wood is very light weight, but didn't sound too bad. It does not have a Grenadilla sound, all in all not too off. The bore is very rough and that can make a difference too”;

Group b (general testers)

3. “Stuffy middle c. Clear throat tones. Thin and slightly stuffy upper register. Clarinet feels rough. Altissimo is inconsistent and difficult to achieve”;
4. “Dark tone, feels good”;
5. “Silky sound”;
6. “Thins out after g above the staff. Wide spread tone.”;
7. “The low register has a dark and rich sound but the upper register sounds more bright and a little shallow. Overall, I love the feel and it responds fine. I just don't like the two contrasting sound qualities”;
8. “Very weedy, very shaky”;

Group c (players)

9. “Hard to play”;
10. “The bottom at the middle register were very good, top register was hard to play”;
11. “Also sharp, more consistent”;
12. “When play with the lowest notes, middle range is good”;
13. “Still has some roughness, but like how light it is. Roughness around the keys makes some raspy sounds, upper register still little flat”;
14. “Response issues with middle b, throat bright sharp above break, notes are flat”;

15. “Lower register sounds good”;
16. “Feels rough texture, some notes harder to play”;
17. “Sound quality muddy, high notes don't speak; very out of tone, no response”;
18. “Less fuzzy noise, top part need to improve surface finish, less stable in high range; good tone”.

Maple (Untreated):

Group a (in-house testers)

1. “Like a sock”;
2. “Could not get any good quality sound from this one at all”;

Group b (general testers)

3. “Tone holes are pretty clean. Stuffy sound”;
4. “Stuffy, quiet sound throughout range. Difficult to project”;
5. “Hardly plays”;
6. “Muffled over break, intonation funky”;
7. “Some notes were very resonant, but others were stuffy and very out of tune”;
8. “Higher register isn't very good. Starts out thin after e”;
9. “Upper register is flat and not responsive”;
10. “About unusable notes”;

Group c (players)

11. “Playable, very hard to blow”;
12. “Bottom register was good, middle register was flat, high notes did not come out”;
13. “Difficult to play, consistent”;
14. “Really difficult to produce good tone”;
15. “Have to overblow upper register; little flat and unresponsive”;
16. “No response above high b”;
17. “Hard to play”;
18. “Upper octaves hard to produce sound”;

19. “Poor tone quality all around, high notes sound airy, low notes boring, no richness to sound like others”;
20. “Lose stability in high range, can't play high range, tone different in low range”.

Yellow-poplar (Treated & Dyed):

Group a (in-house testers)

1. “Very stuffy, as you play up the pitch keeps getting flatter”;
2. “Could get no sound from this one. Tight fit to joints”;

Group b (general testers)

3. “Muffled tone in all registers. Difficult to play throughout range despite air speed”;
4. “Yuck!”;
5. “Hard over break, weird w/tonguing”;
6. “Resistant. Thins out after the register change. Tone production is difficult after f”;
7. “Stuffy and resistant”;
8. “Upper register is not responsive”;
9. “Stuffy”;

Group c (players)

10. “The bottom middle register was hard to play, high notes did not come out”;
11. “Hart to play; inconsistent tuning”
12. “Love the blue again, very difficult to play, could not easily get above middle e, descending in alternative range very difficult”;
13. “Like how it looks/ feels, but no response in upper register”;
14. “Muffled, no response above high g, I like the blue color”;
15. “Hard to play (flat)”;
16. “Notes using lower keys hard to play, wave when they come out”;
17. “Great looking, good feel in hand, keys work well, poor sand quality, very airy buzzy; high notes very shrill, no rich sound”;
18. “Good tone in middle & low, can't play high tone, lose stability in high range”.

Grenadilla:

Group a (in-house testers)

1. “Feels like normal intermediate clarinet”;
2. “Sounds good in all ranges. Wood feels very solid. Close grain pattern. If it is not Grenadilla it sure is a good imitation. Fit is good - no indication of swelling or shrinking”;

Group b (general testers)

3. “Good tone and color”;

Group c (players)

4. “All notes came out, sound was rich, no flat notes”;
5. “Really good quality”;
6. “Heavier, more consistent, prettier sound”;
7. “Easier to play than all the other, more of what I need to, tell key well”;
8. “Still has bright tone, but very responsive, very heavy”;
9. “Throat tones slightly unresponsive middle g and c are sharp”;
10. “Very easy to play, sounds great, keys not so responsive”;
11. “Sometimes is wrong instrument pad not sealing, cannot produce sound on many notes below staff c, instrument would be fun to play if working properly”;
12. “Great sound; good intermediate clarinet”.

ABS Plastic:

Group a (in-house testers)

1. “Nice abs student clarinet”;
2. “Obviously the control group. Plays the way a plastic clarinet plays. Look like a plastic clarinet looks”;

Group b (general testers)

3. “Good control”;

Group c (players)

4. “All notes came out as well, sound was rich as well, no flat notes”;
5. “Also consistent, aside from c/d key, nice tone”;
6. “Not a big fan of plastic clarinet, tone quality not as well, a lot of uneven the range”;
7. “Brighter than 10 but definitely playable”;
8. “Bad response a high g, high notes don't resonate well”;
9. “Can tell that it is plastic”;
10. “I don't like plastic feel”;

11. “Feels cheap in hand, knew it was plastic will be okay for marching band, other outdoor activities, good to learn on tone overall sound quality merges”;
12. “Good clarinet, easy to play”.

APPENDIX C. TUKEY & MANN-WHITNEY TEST RESULTS

Table A.1 *Tukey Test for appearance*

Pairwise comparisons of means with equal variances over: **Clarinet Type/APPEARANCE**

Number of Comparisons				
Clarinet Type 55				
Appearance Contrast	Standard	Error	Tukey t P>t	Tukey {95% Conf. Interval}
Clarinet Type				
Grenadilla vs Yellow Poplar Treated	1.986111	0.3571351	5.56 0.000	.825203 3.147019
Plastic (ABS) vs Yellow Poplar Treated	1.479167	0.3696699	4.00 0.004	.2775127 2.680821
Grenadilla vs Maple (Treated&Dyed)	0.8844444	0.3540607	2.50 0.311	-.26647 2.035359
Plastic (ABS) vs Maple (Treated&Dyed)	0.3775	0.3667006	1.03 0.994	-.814502 1.569502
Grenadilla vs Treated Maple	1.361111	0.3571351	3.81 0.008	.200203 2.522019
Plastic (ABS) vs Treated Maple	0.8541667	0.3696699	2.31 0.430	-.347487 2.055821
Grenadilla vs Treated Maple II	0.9444444	0.3571351	2.64 0.232	-.216464 2.105353
Plastic (ABS) vs Treated Maple II	0.4375	0.3696699	1.18 0.984	-.764154 1.639154
Grenadilla vs Cherry (Treated)	0.9861111	0.3571351	2.76 0.180	-.174797 2.147019
Plastic (ABS) vs Cherry (Treated)	0.4791667	0.3696699	1.30 0.969	-.722487 1.680821
Grenadilla vs Walnut (Untreated)	1.080808	0.3640258	2.97 0.109	-.102499 2.264115
Plastic (ABS) vs Walnut (Untreated)	0.5738636	0.3763312	1.52 0.910	-.649444 1.797171

Grenadilla vs Walnut II (Untreated)	0.6618357	0.3604471	1.84	0.757	-.509838	1.83351
Plastic (ABS) vs Walnut II (Untreated)	0.1548913	0.3728706	0.42	1.000	-1.05717	1.366949
Grenadilla vs Maple (Untreated)	1.527778	0.3571351	4.28	0.001	.3668697	2.688686
Plastic (ABS) vs Maple (Untreated)	1.020833	0.3696699	2.76	0.180	-.180821	2.222487
Grenadilla vs Yellow Poplar (Treated&Dyed)	1.05314	0.3604471	2.92	0.123	-.118534	2.224814
Plastic (ABS) vs Yellow Poplar (Treated&Dyed)	0.5461957	0.3728706	1.46	0.930	-.665863	1.758254
Plastic (ABS) vs Grenadilla	-0.506944	0.3935437	-1.29	0.970	-1.78620	.7723139

According to Table 4.18, when compared with plastic (ABS) appearance, Maple (Treated & Dyed) and Maple (Treated) can be potential substitution material for clarinet; When compared with Grenadilla appearance, Maple (Treated) can be potential substitution material for clarinet.

Table A.2 *Tukey Test for touch/feel*

Pairwise comparisons of means with equal variances over: **Clarinet Type/TOUCH&FEEL**

Number of Comparisons

Clarinet Type 55

Touch/Feel Contrast	Standard	Error	Tukey t	P>t	Tukey {95% Conf. Interval}	
Clarinet Type						
Grenadilla vs Yellow Poplar Treated	1.388889	0.3164005	4.39	0.001	.3604361	2.417342
Plastic (ABS) vs Yellow Poplar Treated	.9791667	0.3275056	2.99	0.103	-.085383	2.043716
Grenadilla vs Maple (Treated&Dyed)	0.8222222	0.3136767	2.62	0.244	-.197377	1.841822
Plastic (ABS) vs Maple (Treated&Dyed)	0.4125	0.324875	1.27	0.973	-.643499	1.468499
Grenadilla vs Treated Maple	0.7222222	0.3164005	2.28	0.449	-.306231	1.750675
Plastic (ABS) vs Treated Maple	0.3125	0.3275056	0.95	0.997	-.752049	1.37705
Grenadilla vs Treated Maple II	0.5138889	0.3164005	1.62	0.871	-.514564	1.542342
Plastic (ABS) vs Treated Maple II	0.1041667	0.3275056	0.32	1.000	-.960383	1.168716
Grenadilla vs Cherry (Treated)	1.013889	0.3164005	3.20	0.057	-.014564	2.042342
Plastic (ABS) vs Cherry (Treated)	0.6041667	0.3275056	1.84	0.752	-.460383	1.668716
Grenadilla vs Walnut (Untreated)	1.135266	0.3193347	3.56	0.019	.097275	2.173256
Plastic (ABS) vs Walnut (Untreated)	0.7255435	0.3303412	2.20	0.510	-.3482233	1.79931
Grenadilla vs Walnut II (Untreated)	1.004831	0.3193347	3.15	0.067	-.033159	2.042821

Table A.2 continued

Plastic (ABS) vs Walnut II (Untreated)	0.5951087	0.3303412	1.80	0.778	-.478658	1.668875
Grenadilla vs Maple (Untreated)	1.472222	0.3164005	4.65	0.000	.4437695	2.500675
Plastic (ABS) vs Maple (Untreated)	1.0625	0.3275056	3.24	0.051	-.002049	2.12705
Grenadilla vs Yellow Poplar (Treated&Dyed)	1.222222	0.3193347	3.83	0.008	.1842318	2.260213
Plastic (ABS) vs Yellow Poplar (Treated&Dyed)	0.8125	0.3303412	2.46	0.334	-.261266	1.886267
Plastic (ABS) vs Grenadilla	-0.409722	0.3486563	-1.18	0.985	-1.54302	.7235775

According to Table 4.19, when compared with plastic(ABS) touch/feel, Yellow-poplar (Treated), Maple (Treated & Dyed), Maple (Treated), Cherry (Treated), Walnut (Untreated), and Yellow-poplar (Treated & Dyed) can be potential substitution material for clarinet; When compared with Grenadilla touch/feel, Maple (Treated & Dyed), Maple (Treated), and Walnut (Untreated) can be potential substitution material for clarinet.

Table A.3 *Tukey Test for tone/sound*

Pairwise comparisons of means with equal variances over: **Clarinet Type/TONE/SOUND**					
Number of Comparisons					
Clarinet Type 55					
Tone/Sound Contrast	Standard	Error	Tukey t	Tukey P>t	Tukey {95% Conf. Interval}
Clarinet Type					
Grenadilla vs Yellow Poplar Treated	2.638889	0.2920892	9.03	0.000	1.689498 3.588279
Plastic (ABS) vs Yellow Poplar Treated	2.333333	0.3023411	7.72	0.000	1.350621 3.316046
Grenadilla vs Maple (Treated&Dyed)	0.6955556	0.2895748	2.40	0.370	-.245662 1.636773
Plastic (ABS) vs Maple (Treated&Dyed)	0.39	0.2999126	1.30	0.968	-.584819 1.364819
Grenadilla vs Treated Maple	0.5138889	0.2920892	1.76	0.803	-.4355016 1.463279
Plastic (ABS) vs Treated Maple	0.2083333	0.3023411	0.69	1.000	-.774379 1.191046
Grenadilla vs Treated Maple II	0 .7222222	0.2920892	2.47	0.326	-.227168 1.671613
Plastic (ABS) vs Treated Maple II	0.4166667	0.3023411	1.38	0.953	-.566045 1.399379
Grenadilla vs Cherry (Treated)	2.575556	0.2895748	8.89	0.000	1.634338 3.516773
Plastic (ABS) vs Cherry (Treated)	2.27	0.2999126	7.57	0.000	1.295181 3.244819
Grenadilla vs Walnut (Untreated)	1.44686	0.294798	4.91	0.000	.488665 2.405055
Plastic (ABS) vs Walnut (Untreated)	1.141304	0.3049588	3.74	0.010	.1500834 2.132525
Grenadilla vs Walnut II (Untreated)	1.359903	0.294798	4.61	0.000	.4017085 2.318098

Table A.3 continued

Plastic (ABS) vs Walnut II					.0631269
(Untreated)	1.054348	0.3049588	3.46	0.027	2.045569
Grenadilla vs Maple					1.564498
(Untreated)	2.513889	0.2920892	8.61	0.000	3.463279
Plastic (ABS) vs Maple					
(Untreated)	2.208333	0.3023411	7.30	0.000	1.225621
					3.191046
Grenadilla vs Yellow					
Poplar (Treated&Dyed)	2.44686	0.294798	8.30	0.000	1.488665
					3.405055
Plastic (ABS) vs Yellow					
Poplar (Treated&Dyed)	2.141304	0.3049588	7.02	0.000	1.150083
					3.132525
Plastic (ABS) vs Grenadilla	-0.305555	0.3218667	-0.95	0.997	-1.351733 7406218

According to Table 4.20, when compared with plastic (ABS) tone/sound, Maple (Treated & Dyed) and Maple (Treated) can be potential substitution material for clarinet; When compared with Grenadilla tone/sound, Maple (Treated & Dyed) and Maple (Treated) can be potential substitution material for clarinet.

Table A.4*Tukey Test for quality*

Pairwise comparisons of means with equal variances over: **Clarinet Type/QUALITY**						
Number of Comparisons						
Clarinet Type 55						
			Tukey		Tukey	
Quality Contrast	Standard	Error	t	P>t	{95% Conf. Interval}	
Clarinet Type						
Grenadilla vs Yellow Poplar Treated	2.597222	0.2865569	9.06	0.000	1.665618	3.528826
Plastic (ABS) vs Yellow Poplar Treated	2.104167	0.2966146	7.09	0.000	1.139865	3.068468
Grenadilla vs Maple (Treated&Dyed)	0.7755556	0.2840901	2.73	0.193	-.1480289	1.69914
Plastic (ABS) vs Maple (Treated&Dyed)	0.2825	0.2942321	0.96	0.997	-.674056	1.239056
Grenadilla vs Treated Maple	0.6388889	0.2865569	2.23	0.486	-.292715	1.570493
Plastic (ABS) vs Treated Maple	0.1458333	0.2966146	0.49	1.000	-.818468	1.110135
Grenadilla vs Treated Maple II	0.7077295	0.2892143	2.45	0.342	-.232514	1.647973
Plastic (ABS) vs Treated Maple II	0.2146739	0.2991827	0.72	1.000	-.757977	1.187325
Grenadilla vs Cherry (Treated)	2.272947	0.2892143	7.86	0.000	1.332703	3.21319
Plastic (ABS) vs Cherry (Treated)	1.779891	0.2991827	5.95	0.000	.8072404	2.752542
Grenadilla vs Walnut (Untreated)	1.44686	0.2892143	5.00	0.000	.5066164	2.387103
Plastic (ABS) vs Walnut (Untreated)	0.9538043	0.2991827	3.19	0.060	-.018847	1.926455
Grenadilla vs Walnut II (Untreated)	1.18599	0.2892143	4.10	0.003	.2457468	2.126234

Table A.4 continued

Plastic (ABS) vs Walnut II (Untreated)	0.6929348	0.2991827	2.32	0.427	-.279716	1.665586
Grenadilla vs Maple (Untreated)	2.180556	0.2865569	7.61	0.000	1.248952	3.11216
Plastic (ABS) vs Maple (Untreated)	1.6875	0.2966146	5.69	0.000	.7231982	2.651802
Grenadilla vs Yellow Poplar (Treated&Dyed)	2.246032	0.2951987	7.61	0.000	1.286333	3.205731
Plastic (ABS) vs Yellow Poplar (Treated&Dyed)	1.752976	0.3049715	5.75	0.000	7615056	2.744447
Plastic (ABS) vs Grenadilla	-0.493055	0.3157703	-1.56	0.897	1.519633	.5335221

According to Table 4.21, when compared with plastic (ABS) quality, Maple (Treated & Dyed), Maple (Treated), and Walnut (Untreated) can be potential substitution material for clarinet; When compared with Grenadilla quality, Maple (Treated & Dyed) and Maple (Treated) can be potential substitution material for clarinet.

Mann-Whitney Test:

Table A.5 *Mann-Whitney Test*

Null hypothesis	H_0: $\eta_1 - \eta_2 = 0$	
Alternative hypothesis	H_1: $\eta_1 - \eta_2 \neq 0$	
Method	W-Value	P-Value
YPopT-App, Grenadilla-App		
Not adjusted for ties	330.50	<0.001
Adjusted for ties	330.50	<0.001
MapleTD-App, Grenadilla-App		
Not adjusted for ties	460.00	0.028
Adjusted for ties	460.00	0.020
MapleT2-App, Grenadilla-App		
Not adjusted for ties	407.50	0.006
Adjusted for ties	407.50	0.004
CherryT-App, Grenadilla-App		
Not adjusted for ties	370.50	0.030
Adjusted for ties	370.50	0.021
MapleUT-App, Grenadilla-App		
Not adjusted for ties	384.50	0.001
Adjusted for ties	384.50	0.001
YPopTD-App, Grenadilla-App		
Not adjusted for ties	376.50	0.005
Adjusted for ties	376.50	0.004
YPopT-App, Plastic(ABS)-App		
Not adjusted for ties	355.00	<0.001
Adjusted for ties	355.00	<0.001
MapleTD-App, Plastic(ABS)-App		
Not adjusted for ties	502.50	0.557
Adjusted for ties	502.50	0.541
MapleT-App, Plastic(ABS)-App		
Not adjusted for ties	412.50	0.029

Adjusted for ties	412.50	0.024
MapleT2-App, Plastic(ABS)-App		
Not adjusted for ties	448.50	0.235
Adjusted for ties	448.50	0.211
CherryT-App, Plastic(ABS)-App		
Not adjusted for ties	408.50	0.554
Adjusted for ties	408.50	0.538
WalnutUT-App, Plastic(ABS)-App		
Not adjusted for ties	385.50	0.204
Adjusted for ties	385.50	0.180
WalnutUT2-App, Plastic(ABS)-App		
Not adjusted for ties	444.00	0.658
Adjusted for ties	444.00	0.639
MapleUT-App, Plastic(ABS)-App		
Not adjusted for ties	414.00	0.032
Adjusted for ties	414.00	0.028
YPopTD-App, Plastic(ABS)-App		
Not adjusted for ties	419.00	0.248
Adjusted for ties	419.00	0.226
Grenadilla-App, Plastic(ABS)-App		
Not adjusted for ties	362.50	0.105
Adjusted for ties	362.50	0.080
YPopT-TouchFeel, Grenadilla-TouchFeel		
Not adjusted for ties	366.00	<0.001
Adjusted for ties	366.00	<0.001
MapleT2-TouchFeel, Grenadilla-TouchFeel		
Not adjusted for ties	451.00	0.101
Adjusted for ties	451.00	0.085
MapleTD-TouchFeel, Grenadilla-TouchFeel		
Not adjusted for ties	898.00	0.014
Adjusted for ties	898.00	0.011

MapleT-TouchFeel, Grenadilla-TouchFeel		
Not adjusted for ties	4299.00	0.008
Adjusted for ties	4299.00	0.006
CherryT-TouchFeel, Grenadilla-TouchFeel		
Not adjusted for ties	397.00	0.003
Adjusted for ties	397.00	0.002
WalnutUT-TouchFeel, Grenadilla-TouchFeel		
Not adjusted for ties	364.00	0.002
Adjusted for ties	364.00	0.001
WalnutUT2-TouchFeel, Grenadilla-TouchFeel		
Not adjusted for ties	373.00	0.004
Adjusted for ties	373.00	0.003
MapleUT-TouchFeel, Grenadilla-TouchFeel		
Not adjusted for ties	355.00	<0.001
Adjusted for ties	355.00	<0.001
YPopTD-TouchFeel, Grenadilla-TouchFeel		
Not adjusted for ties	352.00	<0.001
Adjusted for ties	352.00	<0.001
Plastic(ABS)-TouchFeel, Grenadilla-TouchFeel		
Not adjusted for ties	251.00	0.325
Adjusted for ties	251.00	0.298
YPopT-TouchFeel, Plastic(ABS)-TouchFeel		
Not adjusted for ties	395.00	0.008
Adjusted for ties	395.00	0.005
MapleTD-TouchFeel, Plastic(ABS)-TouchFeel		
Not adjusted for ties	932.00	0.198
Adjusted for ties	932.00	0.184
MapleT-TouchFeel, Plastic(ABS)-TouchFeel		
Not adjusted for ties	4377.50	0.184
Adjusted for ties	4377.50	0.163
MapleT2-TouchFeel, Plastic(ABS)-TouchFeel		

Not adjusted for ties	474.00	0.629
Adjusted for ties	474.00	0.612
CherryT-TouchFeel, Plastic(ABS)-TouchFeel		
Not adjusted for ties	426.00	0.071
Adjusted for ties	426.00	0.059
WalnutUT-TouchFeel, Plastic(ABS)-TouchFeel		
Not adjusted for ties	388.50	0.043
Adjusted for ties	388.50	0.036
WalnutUT2-TouchFeel, Plastic(ABS)-TouchFeel		
Not adjusted for ties	396.50	0.072
Adjusted for ties	396.50	0.061
MapleUT-TouchFeel, Plastic(ABS)-TouchFeel		
Not adjusted for ties	385.50	0.003
Adjusted for ties	385.50	0.002
YPopTD-TouchFeel, Plastic(ABS)-TouchFeel		
Not adjusted for ties	380.50	0.024
Adjusted for ties	380.50	0.018
YPopT-ToneSound, Grenadilla-ToneSound		
Not adjusted for ties	322.00	<0.001
Adjusted for ties	322.00	<0.001
MapleTD-ToneSound, Grenadilla-ToneSound		
Not adjusted for ties	458.50	0.025
Adjusted for ties	458.50	0.017
MapleT-ToneSound, Grenadilla-ToneSound		
Not adjusted for ties	444.00	0.069
Adjusted for ties	444.00	0.058
MapleT2-ToneSound, Grenadilla-ToneSound		
Not adjusted for ties	436.00	0.043
Adjusted for ties	436.00	0.035
CherryT-ToneSound, Grenadilla-ToneSound		
Not adjusted for ties	359.50	<0.001

Adjusted for ties	359.50	<0.001
WalnutUT-ToneSound, Grenadilla-ToneSound		
Not adjusted for ties	348.50	<0.001
Adjusted for ties	348.50	<0.001
WalnutUT2-ToneSound, Grenadilla-ToneSound		
Not adjusted for ties	347.00	<0.001
Adjusted for ties	347.00	<0.001
MapleUT-TouneSound, Grenadilla-ToneSound		
Not adjusted for ties	325.00	<0.001
Adjusted for ties	325.00	<0.001
YPopTD-ToneSound, Grenadilla-ToneSound		
Not adjusted for ties	301.50	<0.001
Adjusted for ties	301.50	<0.001
Plastic(ABS)-ToneSound, Grenadilla-ToneSound		
Not adjusted for ties	242.50	0.202
Adjusted for ties	242.50	0.174
YPopT-ToneSound, Plastic(ABS)-ToneSound		
Not adjusted for ties	310.00	<0.001
Adjusted for ties	310.00	<0.001
MapleTD-ToneSound, Plastic(ABS)-ToneSound		
Not adjusted for ties	485.50	0.297
Adjusted for ties	485.50	0.267
MapleT-ToneSound, Plastic(ABS)-ToneSound		
Not adjusted for ties	466.00	0.481
Adjusted for ties	466.00	0.459
MapleT2-ToneSound, Plastic(ABS)-ToneSound		
Not adjusted for ties	457.00	0.341
Adjusted for ties	457.00	0.321
CherryT-ToneSound, Plastic(ABS)-ToneSound		
Not adjusted for ties	348.50	<0.001
Adjusted for ties	348.50	<0.001

WalnutUT-ToneSound, Plastic(ABS)-ToneSound		
Not adjusted for ties	354.00	0.003
Adjusted for ties	354.00	0.002
WalnutUT2-ToneSound, Plastic(ABS)-ToneSound		
Not adjusted for ties	354.50	0.003
Adjusted for ties	354.50	0.002
MapleUT-TouneSound, Plastic(ABS)-ToneSound		
Not adjusted for ties	311.50	<0.001
Adjusted for ties	311.50	<0.001
YPopTD-ToneSound, Plastic(ABS)-ToneSound		
Not adjusted for ties	288.00	<0.001
Adjusted for ties	288.00	<0.001
YPopT-Quality, Grenadilla-Quality		
Not adjusted for ties	317.50	<0.001
Adjusted for ties	317.50	<0.001
MapleTD-Quality, Grenadilla-Quality		
Not adjusted for ties	450.00	0.014
Adjusted for ties	450.00	0.010
MapleT-Quality, Grenadilla-Quality		
Not adjusted for ties	435.50	0.042
Adjusted for ties	435.50	0.035
MapleT2-Quality, Grenadilla-Quality		
Not adjusted for ties	408.00	0.050
Adjusted for ties	408.00	0.042
CherryT-Quality, Grenadilla-Quality		
Not adjusted for ties	310.50	<0.001
Adjusted for ties	310.50	<0.001
WalnutUT-Quality, Grenadilla-Quality		
Not adjusted for ties	332.50	<0.001
Adjusted for ties	332.50	<0.001
WalnutUT2-TQuality, Grenadilla-Quality		

Not adjusted for ties	354.00	0.001
Adjusted for ties	354.00	<0.001
MapleUT-Quality, Grenadilla-Quality		
Not adjusted for ties	332.00	<0.001
Adjusted for ties	332.00	<0.001
YPopTD-Quality, Grenadilla-Quality		
Not adjusted for ties	253.00	<0.001
Adjusted for ties	253.00	<0.001
Plastic(ABS)-Quality, Grenadilla-Quality		
Not adjusted for ties	232.00	0.101
Adjusted for ties	232.00	0.084
YPopT-Quality, Plastic(ABS)-Quality		
Not adjusted for ties	311.00	<0.001
Adjusted for ties	311.00	<0.001
MapleTD-Quality, Plastic(ABS)-Quality		
Not adjusted for ties	498.00	0.479
Adjusted for ties	498.00	0.449
MapleT-Quality, Plastic(ABS)-Quality		
Not adjusted for ties	474.50	0.639
Adjusted for ties	474.50	0.624
MapleT2-Quality, Plastic(ABS)-Quality		
Not adjusted for ties	444.00	0.658
Adjusted for ties	444.00	0.644
CherryT-Quality, Plastic(ABS)-Quality		
Not adjusted for ties	310.00	<0.001
Adjusted for ties	310.00	<0.001
WalnutUT-Quality, Plastic(ABS)-Quality		
Not adjusted for ties	360.50	0.005
Adjusted for ties	360.50	0.003
WalnutUT2-TQuality, Plastic(ABS)-Quality		
Not adjusted for ties	387.50	0.040

Adjusted for ties	387.50	0.030
MapleUT-Quality, Plastic(ABS)-Quality		
Not adjusted for ties	338.50	<0.001
Adjusted for ties	338.50	<0.001
YPopTD-Quality, Plastic(ABS)-Quality		
Not adjusted for ties	255.50	<0.001
Adjusted for ties	255.50	<0.001