Preserving Venice's Bells and Their Towers

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Abstract

In Venice, where Catholic Church attendance has declined, bells and bell towers have lost their purpose. Their neglect has left them vulnerable to decay and structural stresses. This project involved complex onsite surveys of 20 bell towers and their 69 bells. Analysis of condition, accessibility, and safety for the public was documented for each tower. Two thirds of the towers are in poor to fair condition, but some percentage can be made safe with proper repairs. Photos, dimensions, 3D models, audio, and other bell tower data were documented in an online application. Recommendations and concept designs for merchandise were also researched in order to establish an outline for preservation. We are hopeful that our work has been beneficial in helping preserve the historic bells and bell towers of Venice and reconnecting them to the public.

Executive Summary

Within Venice and its lagoon there are 118 bell towers, Figure 1. Venetian bells are iconic pieces of the city's cultural history. Their surfaces are inscribed with rich detail about the communities in which they are rung. Their musicality is a form of public art, and they were used to signal danger, call church goers to worship, announce celebrations, and mark times of war. Today, Venice's bells and the towers that house them are historical landmarks that help locals and visitors navigate throughout the narrow streets of Venice. Despite their value, however, these aging bells and bell towers that can date back all the way to the seventh century, are often in states of disrepair. Many are being neglected due to disuse, a decline in church attendance and funding, and their replacement with technologies such as wristwatches, GPS, and other communication systems. Neglected bells and bell towers have become vulnerable to corrosion, cracking, and rotting wood supports, thus reducing the musical quality of the bells and making the structures themselves dangerous and inaccessible.

In order to preserve these important Venetian structures, it is important to further understand their current state. In 1992 the Venice Project Center began collecting data on the bells and bell towers, and as of 2013, had mapped and collected information on over half of these towers in the region, including field note data on dimensions and features, photographs, and some audio recordings. Because this data was incomplete, and in some cases outdated (because new technologies now allow for more rigorous data collection), this project aimed to update and complete data collection on the bells and bell towers on the Vicariate of Cannaregio and the northern lagoon. In total, we were able to visit and document complete information on 20 bell towers during our seven week stay in Venice from November 5th to December 6th. We collected data on the exterior of each bell tower as well as the interior shaft, including its walls, supports, landings, belfry, and specifically the bells within the belfry. In order to publicize this information to online applications such as Venipedia, the Bells Application at bells.veniceprojectcenter.org, and the Cartography application, and to draw conclusions about the conditions, accessibility, and features of these artifacts, we collected over 9,000 pictures for photogrammetric reconstruction. From these, we made over 48 3D models of Venetian bells that will be valuable resources for further analysis. We were also able to produce 3D belfry and shaft models when the belfry and shaft of the towers were clear.

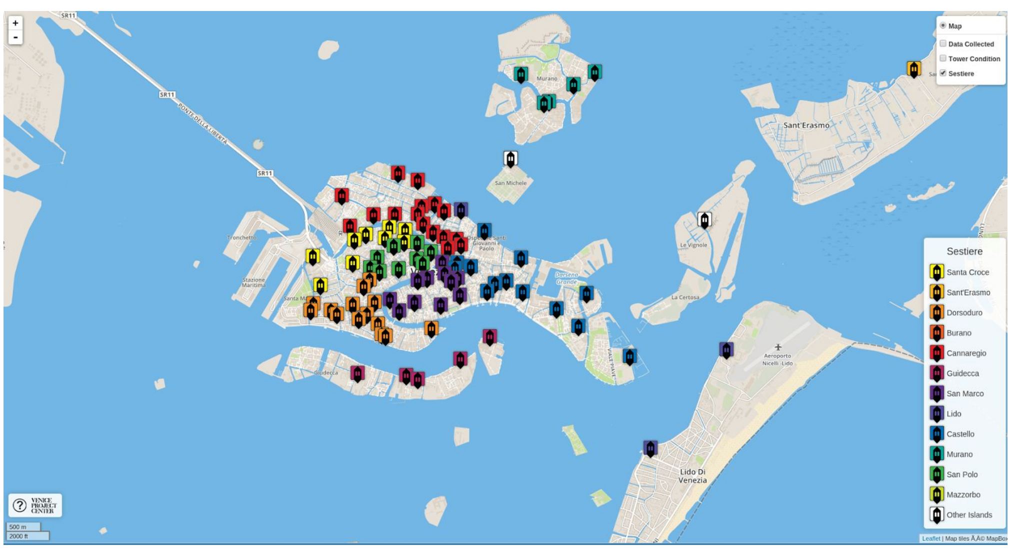
Our four objectives, over the course of the term, were to update and organize the current inventory of bell towers, update and organize the current inventory of bells, publicize information and develop a plan to allow for future updates, and to create an outline for the long term preservation of these structures. We were able to accomplish the first two objectives by conducting field work for a month and a half. As a team we were able to concisely update and expand upon data collection for the 20 bell towers we had the opportunity to visit. GoPro ascended videos, bell sound audio, and pictures used for panoramas, photogrammetry, and overall analysis were collected for each of the towers and their bells. The technology used for all this data collection was the latest, especially for audio recording, and the quality was greatly improved from previous project years. This quality of data collection was essential to our publicizing objective because the panoramas, 3D models, and specific pictures of the exterior, shaft, and belfry would be used for the various applications that we developed. The sound recorder was crucial to our sound documentation for each individual bell due to its sophisticated design. By recording the ringing of each bell in the tower we were able to identify, through software, the musical note and frequency of the bell.

Towers were analyzed based on their key characteristics which were given weights when determining the overall safety of the tower. Safety of the landings was worth 20%, the belfry 16%, the vibrational assessment and tilt were each 14%, frame type and quantity of cracks and holes were each 12%, and the damaged bricks and tie bands were each 6%. These percents were then multiplied by their respective ratings (1-5) and once added together they then rounded to the nearest whole number to produce a safety rating that for the tower. Eleven towers received a safety rating lower than five, six towers were given a safety rating of five, and the remaining four towers were not evaluated since they were public towers or inaccessible to the team.

To determine the accessibility of each staircase within the tower, a similar rating (1-5) was given based on both sturdiness and clutter. This rating system also took into account if the landings were being used as storage space, and if they were, whether such storage impeded walkways. Another factor of accessibility taken into account was how easy it was to climb up the tower. If these landings were cluttered with supplies and had many obstructions, the level of accessibility for the tower immediately declined. Some towers had natural lighting for the landings with windows, but this still was not enough to provide for a proper climbing experience. Once we reached the landing before the belfry, we paid special attention to the difficulty of entering the belfry. Bell towers that had a set of stairs with a railing leading to the belfry could be considered accessible. Based on all this qualitative and quantitative data we were able to determine overall accessibility ratings for each of the 20 towers visited. Three out of the 20 bell towers received a rating of a one, three were given a rating of a two, four were given a rating of a three, two were given a rating of a four, and five were given a rating of a five.

After collecting the information on both bells and bell towers, we organized it into a machine-readable spreadsheet, which allowed us to transfer the information into online applications such as

- "Venipedia" - A wiki containing information on Venice. All of the towers visited by this group already had their own Venipedia pages before the project started, so the team simply updated the displayed information for each page and modified the template. These updates included new photos, links to other applications, and factual information on external and internal data.
- Bells Application, bells.veniceprojectcenter.org - An application created by past groups to display more interactive forms of data such as panoramas and audio in a more engaging way. The team focused their time on updates for this application.



- Cartography Application, cartography.veniceprojectcenter.org - An application used to display six archaic maps of Venice, functioned by storing a number of layers for each catographic map that could be toggled to highlight different points of interest. This application was modified to accurately display the 20 towers that we visited on the first four archaic maps of Venice.

In addition to publicizing this newly collected data, we also researched and developed plans for preserving, promoting, and raising funds for historical artifacts like bells. After reviewing what other organizations have done, we further explored several possibilities, including donation/collection boxes, audio tours, and merchandising (including sale of ringtones and bell souvenirs) for the purpose of fundraising and education. We created a set of recommendations and plans that included these strategies and further developed a plan for creating and marketing bell tower keychains. Funds from these keychains would help the churches preserve their towers. A 3D printable bell tower was designed to demonstrate how this technology could be used to support the bell towers.

Ultimately, since the development of this project in 1995, we are the first team to successfully visit 20 towers in the seven week study period. We were able to perform detailed ascended surveys for each of these towers and by doing so were able to analyze our data collection process for future groups. We believe that future studies on the bells and bell towers of Venice will find our data useful, the analysis of our methods of data collection beneficial, and our modifications to user applications helpful in their field work.

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1. Introduction

For centuries, bells have been instrumental in social and religious customs such as signaling danger, marking religious events, communicating time, or making music. Events were often "indicated by the number of rings or, in the case of multiple bells, a sequence of large and small bells."[1] Bells have often been a part of community culture and are frequently housed in iconic towers, but the ancient towers are losing their importance in society. In addition to a decline in church attendance, increasing dependence on other technologies, such as cellular phones and digital clocks, has slowly replaced bells' original purposes, leading to disuse and often neglected upkeep. This in turn causes both bells and their respective towers to fall victim to the elements as time passes. For their historical and cultural value, it is imperative that these historical structures are preserved for future generations to come.

Similar to other cities across the globe, Venice is currently adjusting to the modern-day demands of a constantly advancing society. Venice, about twice the size of New York City's Central Park, contains 118 bell towers in the city and surrounding lagoon.[2] The bells and bell towers have somewhat lost their grand purpose within the Venetian community and as a result, often stand merely as pieces of static, public art. These structures once represented the religious heritage of Venice by symbolizing the people's strength and faithfulness to God. Their purpose was to point toward heaven and act as surveying posts during periods of war. In peaceful times, the bells within the towers rang for marriages and funerals, to keep time, and for Catholic festivals and mass.[3] However, due to current technological advances, most people have replaced the function of bell towers with watches, phones, and the Internet. In addition, statistics have shown a significant decline in the percent of Venetians who regularly attend church, and "only 15% of worshippers attend Mass every Sunday."[4] Over time, the neglect of these bells and bell towers has left them in a state of disrepair and in rare occasions, has led to their collapse. Specifically, these structures are vulnerable to saltwater and sea air, cracking, dripping grease

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[1] Long, Michael P. "Bells." 1989.
[2] Carrera, Fabio. "IQP Team Meeting." 2015.
[3] Howard, Deborah et al. "The Architectural History of Venice." 2002.
[4] Moore, Malcolm. "Italian Church Attendance Lower than Thought." 2007.

from the bell mechanisms, and the surrounding ecosystem. As the towers have aged, the stairs and landings may have decayed, preventing access to the towers to properly maintain and preserve them. With the collapse of the San Marco Bell Tower in the early 20th century, however, researchers and preservationists have begun to study and analyze the bells and and their towers more intensively.

Since 1992, Worcester Polytechnic Institute's (WPI) Venice Project Center (VPC) began documenting the bells and towers and investigating towers' structural integrity and potential value to the public. The initial research groups began as a way to advocate restoration process. The goals of the VPC have been a continuous effort to preserve Venetian culture and educate the public on the significance of bells and their towers.[5] In efforts to address these issues, databases have been produce to store collected information including facts, pictures, measurements, and audio recordings.

While there has been intensive study and progress on developing and expanding the information concerning the bells and bell towers of Venice, there are still many facets of these treasures that have yet to be documented and preserved.[6][7] According to Venipedia, an online website with a repository of information and studies on Venice, data has only been collected on 41 of the 118 bell towers in the lagoon.[8] This means that 65% of all those in the lagoon have yet to be visited and surveyed from within by VPC researchers. However, even without an interior inspection, there remain some aspects of the towers that are captured in the database, such as exterior photographs or the tower's height. One of the most pressing needs is audio and visual data for a number of the towers. Based on information stored within the online Bells Application published by previous project groups, only 3% of the towers had both audio and visual data collected and 84% lack both. Nearly 90% of the towers do not have audio data, although the number of towers capable of ringing is unknown.[9] Additionally, the data captured in audio and visual format is rather outdated; some of the information dates back several years while cameras have steadily improved over the past decade, according to camera benchmarking conducted by

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[5] "Venice Project Center 2.5." Venice Project Center 2.5. Accessed December 16, 2015.
[6] Baruffi et al 2012.
[7] Heinricher et al 2013.
[8] "Bell Towers." Venipedia. Accessed September 21, 2015.
[9] See Bell Towers Data Chart in Appendix A.

DXOMARK.[10] This means that the quality of photographs taken with modern equipment will be much closer to capturing the true nature of the Venetian bells and bell towers. The VPC's Venipedia pages on bells (wiki-like references pages) are in need of updating and refinement to better support and display the newly captured information.

This project promoted the preservation of the Venice bells and bell towers by publicizing their current conditions and developing ways to renew interest. This was accomplished through several steps. The first task was to visit the bell towers to collect new data and correct existing data. These data were then organized into an updated inventory of bells and bell towers accessible on Venipedia and online applications. Meanwhile, methods for raising public funding and repurposing the bells and bell towers were thoroughly investigated before a plan for the long term preservation was created. The group decided to execute the development of tower keychains, as it was the most effective and reasonable idea to pursue.

The goal of this project was to prevent Venetian bells and bell towers from losing any cultural significance within the city's colorful history. We were able to do this by documenting and publishing the data we collected from 20 ascended bell tower surveys. Once all this data was compiled we produced a range of deliverables which were then inserted into the online Bells Application and linked to specific Venipedia pages. Our digital contribution of data allows all current and existing data of bells and bell towers to be accessed by the public.

[10] See Camera Benchmarks over Time in Appendix B.

2. Background

Tower bells have existed through centuries and have been used in many communities around the world. Through their ringing, inscription, and use, they have expressed the unique culture of the amphibious island of Venice in particular. In Venice, bells and their towers have become symbolic objects that defined the identity of this Catholic city. In order to preserve these irreplaceable pieces of art and architecture, they must be documented, and the need for their restoration must be publicized.

To accomplish this, it is crucial for people to understand the importance these structures have within the Venetian society. Appreciation begins with knowledge of bell history, anatomy, foundries where they are produced, acoustics, decorations, supports, and striking methods. Similarly, an appreciation of bell tower structures, their historical functions, neglect, and preservation strategies are necessary.

2.1 Overview of Bells

One of the primary objectives of this project is the preservation of the many bells in the city of Venice. Bells are not unique to Venice. The beginning of bells and bell towers dates back to 130 A.D in China when Chinese philosopher, Chang Heng, invented an earthquake detector, as shown in Figure 1. This mechanism was designed to use an internal pendulum that would swing back and forth based on the Earth's movements.[11]

[11] Tyack, Geo S. (sic) "A Book about Bells", 1898.

Figure 1: Ancient Earthquake Detector

The design of this structure was later converted so the pendulum would hit an instrument to produce sound. From China, this mechanism traveled during the Medieval Ages to Europe, where churches quickly adopted these bells by putting them in towers.

The basic anatomy of a bell is fairly universal. As discussed by Tim Vigin, a sixth generation bell expert, on the top of the bell, there is a wooden crossbeam called a yoke that the bell is attached to, as seen at the top of Figure 2.1. The connecting piece is known as the crown. Commonly made of metal, the crown can be directly attached to the yoke, or the bell can dangle with the crown being tied to a series of leather belts. As shown in Figure 2.2, the head and shoulder of the bell are connected to the crown.[12] The shape of the bell is designed to influence its sound as discussed by Rech Adelheid, a bell sound expert. The top section of a bell is tuned to resonate one octave higher than the hum, the main note the bell is designed to produce. The main section of the bell is referred to as the waist. This is the largest section of the bell and is tuned to resonate at a fifth, or quint, of the hum tone. The bottom section of the bell where the flare begins is known as the sound bow. This section is attached to the lip, the very bottom of the bell, and is responsible for the generation of the hum tone. The open bottom of the bell is the mouth. Within the mouth of the bell the clapper, a metal rod attached to a metal ball is visible. The clapper hangs free from the shell of the bell to invoke independent movements and strike the interior, producing sound.[13]

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[12] Verdin,Tim, "Verdin Bells & Clocks", 2011
[13] Rech, Adelheid. "The Carillon: How It Works." 2014.

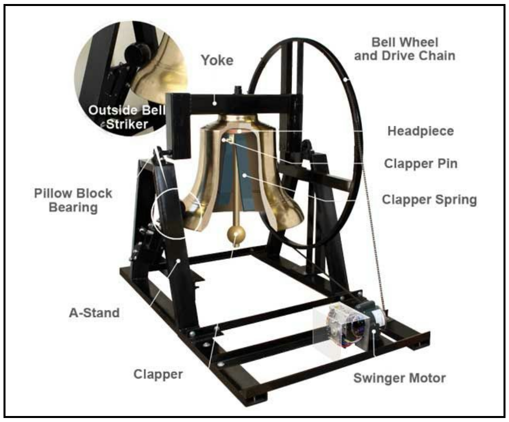

Figure 2.1: Anatomy of a standard bell with supports[14]

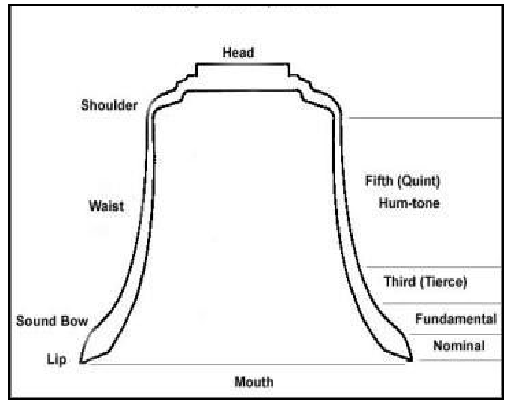

Figure 2.2: Anatomy of standard bell[15]

2.1.1 Bell-Founding

Bell-founding is the art and practice of casting large bells in a foundry, and these bells are then used in churches, clocks, bell towers, and other buildings. The initial process of making a bell was a momentous occasion and required the entire community to collaborate. Bells were forged on site, in holes dug next to the structure being erected.[16]

As Virdin, a bell casting expert, explains, modern bell forging takes place using casting molds and a high copper bronze alloy as seen in Figure 3. The alloy is poured into the mold and pressed until cooled. All inscriptions and artwork found on the bells are usually created in the mold and not done directly on the bell.[17] Functional bells, or bells made to be used, are manufactured out of bronze because it is soft enough to be shaped as desired but also firm enough to prevent the bell from deforming significantly over time with use.[18] Decorative bells can be made of silver, glass or any other materials, but have suboptimal performance results. In addition, by using metal instead of wood or glass, a strong vibration is created that keeps the sound resonating rather than producing a loud, quick decaying tone.[19]

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[14] Verdin, Tim. "Verdin Bells & Clocks", 2011.
[15] Rech, Adelheid. "The Carillon: How It Works." 2014.
[16] Falkenhausen, Lothar Von, “Suspended Music Chime-bells in the Culture of Bronze Age China”, 1993.
[17] Verdin,Tim. "Verdin Bells & Clocks", 2011.
[18] Johnston, R.J, “Bell-ringing: The English Art of Change-ringing. Harmondsworth, Middlesex, England: Viking”, 1986.
[19] Zappas, Kelly, "The Science of Sound: Examining the Role Of Materials in Musical Instruments.".

Figure 3: Bell casting molds[20]

2.1.2 Acoustics of Bells

A bell's ringing, like any other sound, can be broken down to a science. Campanologist W.W Starmer states that the frequency of the waves, and thus the sound generated by the vibration, is directly proportional to the diameter of the bell and the thickness of the metal where the clapper strikes the bell. Bells are made to exact formulas, therefore when a diameter is chosen, it is possible to calculate every remaining dimension of the bell and its musical note or tone. The frequency of a bell's note varies with the square of its thickness, and inversely with its diameter.[21]

If the bell is mounted as cast, it is called a maiden bell. Tuned bells are worked after casting to produce a precise note. The strongest overtones have been tuned to be at octave intervals below the nominal note, however other notes also need to be brought into their proper relationship.[22] Bells are usually tuned via tuning forks or by more modern electronic tuners.

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[20] Andreasdziewior, "Bell Foundry", 2007.
[21] Starmer, W.W., "Bells and Bell Tones", 1901.
[22] "Blagovest Bells: How Bells Are Made."

2.1.3 Bell Decoration

Historian Geo Tyack in *A Book About Bells* explains that most European bells have very similar qualities in terms of decoration and design. These ornate pieces of art usually include an inscription about where or when they were made in addition to an engraving of a religious figure. Typically, bell makers and designers were identified through their unique style of bell design as they were a true reflection of their work and artistic abilities. Some of the most common inscriptions on these bells were of saints, angels, royalty, or the shield of the patron who invested in the church. More commonly, there were inscriptions of whom the bell was dedicated to, who the maker and donor were, the date in which it was cast, and other historical information specific to the bell. A majority of these inscriptions were in Latin, although in Italy it was common for them to be in Italian.[23]

Tyack also explains that although bells were designed similarly, the inscriptions on the bell varied based on the wealth of the sponsor. In some cases his or her name was inscribed artfully on the bell in dedication to their generosity. Inscriptions normally included the current ecclesiastical rulers of the parish at the time of casting. This usage of inscriptions was customary in the seventeenth century bells as the Church leaders would immortalize their names on the bells to be with their church forever.[24]

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[23] Tyack, Geo. S., “Bell Decorations", 1898.
[24] Tyack, Geo. S. “Bell Decorations." 1898.

2.1.4 Supports for Bells

The two common methods for securing bells are known as H-frames and A-frames as discussed in Heywood and Lewis's, *Bell Towers and Bell Hanging, an Appeal to Architects*. H frames are cross beams in the shape of an "H" that attach the bell to the ceiling and outer walls of the tower. Alternatively, H-frames can be stand-alone parallel legs with a single cross beam that holds the bell. An example can be seen in Figure 4.1 where the bell hangs in between the two beams and has its weight redirected into the surrounding walls. In contrast, A-frames are support structures that form the shape of an "A" and attach the bell to the ground of the belfry as shown in Figure 4.2. The momentum of the bell is then transferred into the base of the belfry in contrast to the H-frame.[25]

Figure 4.1: Example of H-Frame support

Figure 4.2: Example of A-Frame support

Another type of bell architecture commonly found in most modern towers is the Carillon. This type of bell setup can be housed in the traditional tower, or sometimes as a freestanding structure, Figure 5.1.[26] A Carillon is a cluster of at least 23 different sized bells that are rung synchronously to form a melody.[27] These structures can be found at many universities and in most cities around the world. The Carillon can be played with a keyboard-like instrument or automated using computer programming or a player piano style roller as seen in Figure 5.2. Some bells have been replaced with speakers which mimic the traditional sounds produced and have a much lower cost of maintenance and setup.

[25] Heywood et al. "Bell Towers and Bell Hanging, an Appeal to Architects."1914.
[26] Rech, Adelheid. "The Carillon: How It Works." 2014.
[27]"Definition of Carillon in English."

Figure 5.1: Carillon[28]

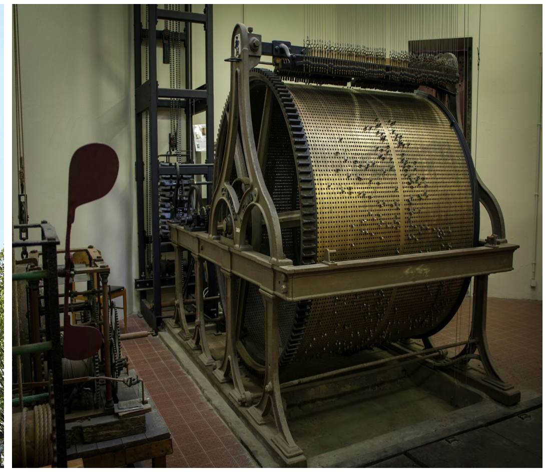

Figure 5.2: Roller with striking pins[29]

2.1.5 Striking Methods

Another key factor in the ringing of the bell is how they are struck. Most common is the swinging method. A rope can be tugged from the ground that causes the entire bell structure to swing back and forth, and inside the bell, a clapper strikes the sides causing vibrations as seen in Figure 6. As discussed by Heywood and Edwin, this method is not advisable in unbalanced systems as it causes a great deal of bell movement, and over time this motion and vibration travel down the tower shaft and may damage the support structure. In addition, unbalanced swinging can leave a skid mark inside the bell formed by the clapper. These vibrations and skiddings can damage the structure and bell thus changing the intended note of the bell and putting strain on the bell tower that could lead to a collapse.[30] The other method is striking the shell of the bell. This causes less structural damage, but over time can leave dents which might deform the bell and alter its sound as seen in Figure 7. The last common method, similar to the hammer method, is to swing the clapper while the bell remains stationary as seen in Figure 8. This method is common to carillons and other bell based instruments, but less likely to be found in a traditional bell tower.

[28] Raupach, Oliver. “Munich Park Carillon.” 2006.
[29] Simonly. “Belgium Belfry Automated system.”
[30] Heywood et al. “Bell Towers and Bell Hanging, an Appeal to Architects.”1914.

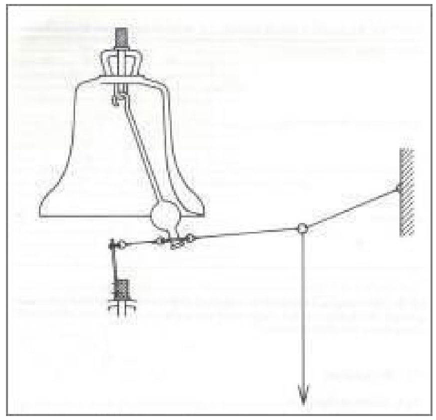

Figure 6: Example of clapper swinging method[31]

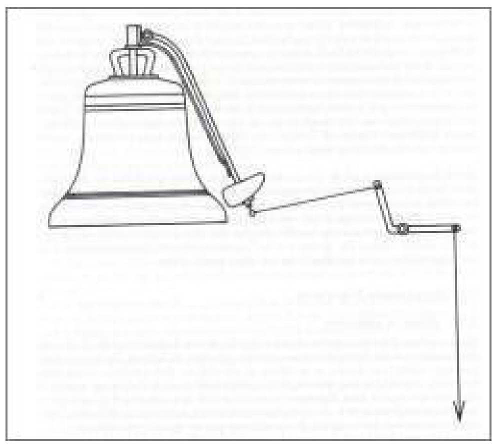

Figure 7: Example of hammer method[32]

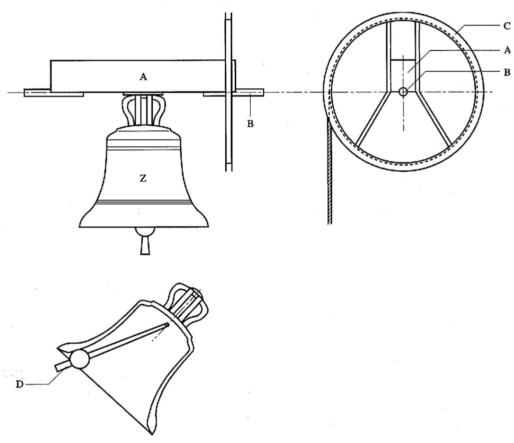

Figure 8: Example of rotation method[33]

[31] Rech, Adelheid. "The Carillon: How It Works." 2014.
[32] Rech, Adelheid. "The Carillon: How It Works." 2014.
[33] Lehr, Andre et al. 2005.

2.2 Overview of Bell Towers

The structures that hoist bells into the sky to enhance their effective range and the projection of their sounds are known as bell towers. Over many centuries the design and aesthetics have changed, but their sole purpose, to house and protect bells remains unchanged.

Figure 9 illustrates the typical layout of a bell tower. Acquired knowledge from the Venice Project Center defines that the bottom of the bell tower is referred to as the base. Embedded into the foundations of the rock beneath it, the base usually contains tensioning supports driven into the ground as well as other stability enhancing measures. The main portion of the tower is known as the shaft. The shaft contains the stairs leading up the tower and functions mostly as empty space leading up to the functional part of the tower, the belfry. The location where the bells are contained is called the belfry, an open area of windows allowing for the sound to project over the surrounding landscape. Above the belfry is the attic and the roof. Held within these areas are usually mechanical workings of the bell or simply empty space.[34] [35]

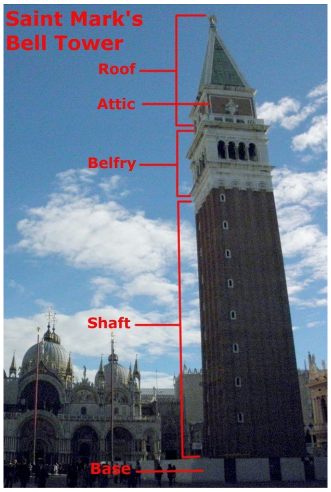

Figure 9: Representation of the anatomy of a traditional campanile, San Marco[36]

[34] Baruffi et al 2012.
[35] Heinricher et al 2013.
[36] "Bell Towers." Venipedia. Accessed September 21, 2015.

2.2.1 Types of Bell Towers

Similar to other types of ancient architecture, bells and bell towers come in a variety of shapes, sizes, architectural designs, and layouts. Commonly, bell towers are imagined as large pillars that extend towards the sky, usually attached to a chapel or other ornate building. Traditional bell towers, also referred to as a campanile a torre, are composed of a base, shaft, belfry, and ceiling as shown above in Figure 9.[37] Within the belfry there are usually three or four large bells that can be manually operated or controlled by an automatic system of pulleys.

Common to many parts of Italy and other Romantic nations is the campanile a vela, also known as the Roman Bell Tower. This name comes from the popularity of arches in Roman architecture. A velas consist of arches with bells that hang from their apex, Figure 10. As stated by historian Linda Alchin, the use of arches was very common during the age of the Roman Empire due to their ease of construction and reliability. Prior to modern material science and engineering designs, large towers and expansive flat ceilings were difficult to erect and maintain. [38] For these reasons the Romans built arches, many of which are still standing today, proving this style of architecture has lasted over many centuries.

Figure 10: San Giacomo, an example of an a vela

[37] "Bell Towers." Venipedia. Accessed September 21, 2015.
[38] Alchin, Linda. "Roman Arches."

Similar to the a vela is the Bell-Gable. The Gable is an arch structure commonly found on top of buildings that houses a bell instead of the traditional tower with a belfry. These buildings are more common to Hispanic countries but follow a similar design to Roman counterparts.

Common in older cities as the centerpiece of town, clock towers allowed for the telling of time anywhere within eyesight of the tower. Clock towers were very helpful before the development of portable clocks, such as wristwatches, and the later widespread use of cellphones. The most famous clock tower in Venice is the San Marco Clock Tower, also known as Torre dell'Orologio, an early Renaissance building on the north side of the Piazza San Marco as shown in Figure 11. The tower contains the archway that leads to the main streets of Venice. This clock was meant to be seen by sea travelers in the lagoon and to display the wealth of Venice.[39]

Figure 11: Clock tower of San Marco Square[40]

2.3 History and Function of Bells in Venice

While bells and bell towers are highly esteemed across the world, in Venice their value has been nearly paramount. Their role in the past has formed an important bond between Venetians and bell towers. However, recent changes in Venetian culture threaten to abandon the

[39] "Torre Dell'Orologio: Story of San Marco Clock Tower." 2015.
[40] Green, Peter. "St. Mark's Clock Tower." 2010.

towers and quicken their demise. Past attempts to preserve these towers have not always been successful, and proper maintenance of many bells is perhaps long overdue.

Early on, the Roman Catholic Church had a strong presence in Venice and the Curia, the governing branch of the Roman Catholic Church, and established a single Diocese in Venice which was divided into 13 regions known as Vicariates.[41] The churches dotting the city were often marked in the skyline by the bell towers which were erected to hold aloft the church bells. In the Catholic Church, these vertical pieces of architecture guided worshippers to church for prayer and celebration. Venetian bells and bell towers are a physical manifestation of culture, symbolizing the relationship between people and their religion. These structures explain the history of Venice while also describing how the society once lived. Due to the dense cityscape of Venice and number of churches spread across many Vicariates, there is a wide range of bell towers and bells that helped make up the identity of this city.[42] These towers were also located on the many islands of the Venice lagoon, as seen in Figure 12, and densely distributed across the city itself, Figure 13.

Figure 12: Bell towers across the Venice Lagoon[43]

[41]Carrera, Fabio. "IQP Team Meeting." 2015.
[42] Ball, Dr. Steven. "The Defense of Bells: Their Use and History in the Roman Liturgy."
[43]"Venice, IT." Map. Google Maps. Google, 11 Dec 2015. Web. 11 Dec 2015.

Figure 13: Bell towers in the center of Venice[44]

In addition to dividing Venice into religious sections, Venice is geographically divided into eight subdivisions, Figure 14, referred to as sestieri that constitute the old city center. Cannaregio is the most populated sestiere and is home to the historic Jewish Ghetto. Located in eastern Venice, Castello is the largest sestiere. Dorsoduro, a larger sestiere, is located across the Accademia Bridge from San Marco and is bounded on one side by the Grand Canal. Near the Rialto bridge is the location of San Polo, while the sestiere of Santa Croce is along the Grand Canal.[45] Numerous bell towers populate each sestiere even though some are located within a short distance from one another.

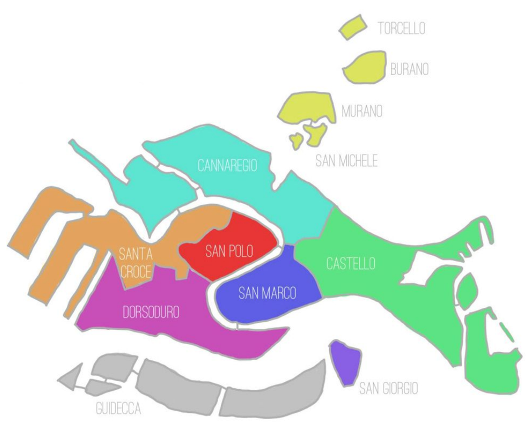

Figure 14: Map of the sestieri in the city of Venice and the Lagoon[46]

[44] "Venice, IT." Map. Google Maps. Google, 11 Dec 2015. Web. 11 Dec 2015.
[45] Salvadore, Pietro."IQP Team Meeting."2015.
[46] "Venice Sestiere." 2011.

Bells have particular spiritual significance as they once stood as a way to call people to worship. Traditionally in Venice, bells sounded three times a day, at 06:00, 12:00, and 18:00, calling upon those with Catholic faith to recite the Lord's Prayer and The Angelus.[47] The Angelus is a short practice of devotion to the Incarnation of Jesus and was initiated at the sound of a bell. The bell ringing at noon signaled meditation on the Passion of Christ and was only rung on Fridays. However, over the years, this bell could be heard to mark every day of the week.[48]

In legends written during the Middle Ages, the bells in their bell towers were "placed like sentinels on the towers, [to] watch over us."[49] These towers "speak and pray for us in the troubles; they inform heave (sic) of the necessities of the earth".[50] During the Middle Ages many thought that the ringing of church bells cleansed the air and prevented lightning storms. The symbolism behind these structures is the ultimate representation of history that tells the story of how Venetian society once lived and what they valued.[51]

2.3.1 Bells in Peril

Secularization contributes to the lack of interest in religious events and icons that once were central to Venetian society. When church attendance declines, the structural integrity of buildings related to the church also begins to decline. Poor attendance leads to cancellation of masses or closing of churches, limiting the need to use the bells to identify when mass will start or if a religious celebration is beginning. Without churchgoers, donations are not being collected for the repair and upkeep the church, causing the buildings to fall into disrepair and the bell towers to become under utilized.

Religious attendance noticeably began to decline during the late twentieth century. A study conducted by Vezzoni and Biolcati-Rinaldi, discovered that only 47% of self-proclaiming Catholic Italian adults attended church weekly in 1968. Until 1981, there was sharp decline in religious participation because Italy went through a Catholic revival through 1999, where the

[47] "Church Bells: Their Use, Their Romance, Their History."1903.
[48] Tyack, Geo. S. (sic) "Bell Decorations."1898.
[49] "Church Bells: Their Use, Their Romance, Their History."1903.
[50] "Church Bells: Their Use, Their Romance, Their History."1903.
[51] "Church Bells: Their Use, Their Romance, Their History."1903.

main goal was to revive attendance. Figure 15, published in their study "Church Attendance and Religious Change in Italy, 1968–2010: A Multilevel Analysis of Pooled Datasets," displays the percent of Italians who attended church on a weekly basis from 1968 to 2010. These data were obtained through a series of church surveys that were pooled and referenced against data collected from individual churches.[52]

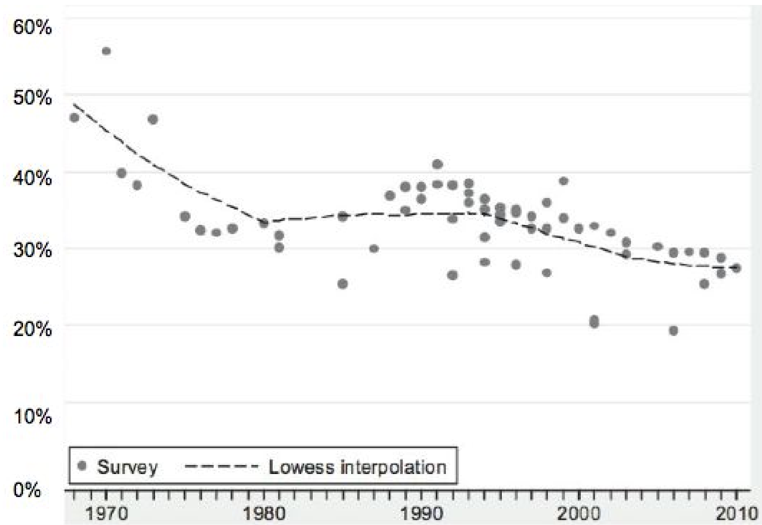

Figure 15: The percent of Italians attending church over a time period of 42 years[53]

The decline of religious attendance in Venice has had real consequences for the bell towers. They require attention, care, and resources, and if these basic needs are not met, they may not survive as culture changes with time. Tragically, it is no longer a hypothetical question concerning bell tower collapses and their dangers. In 1902 the San Marco bell tower of Venice, located in a highly visited public square, collapsed due to a dangerous crack on the north wall of the tower, Figure 16.[54] Then in 1989, the 900 year-old Pavia bell tower in Italy collapsed and killed three people.[55] There are life-threatening dangers associated with aging masonry towering hundreds of feet above the ground.

[52] Vezzoni et al. "Church Attendance and Religious Change in Italy, 1968-2010: A Multilevel Analysis of Pooled Datasets."
[53] Vezzoni et al. "Church Attendance and Religious Change in Italy, 1968-2010: A Multilevel Analysis of Pooled Datasets."
[54] "Ufficio Stampa Comune Venezia."2014.
[55] Montalbano, William. "900-Year-Old Bell Tower Collapses in Italy; Three Killed." 1989

Figure 16: Bell tower San Marco Bell Tower collapse[56]

2.3.1.1 Previous Attempts to Address the Problem

The Venice Project Center has been collecting data for over 20 years on the bell towers Venice and has recorded partial data on a total of 157 bells. The researchers documented external, internal and bell data including measurements, inscriptions, observable conditions, and videos. There were still many towers unvisited and the grand total of bells within the lagoon is unknown. An estimation of total bells can be made, as each tower often contained an average of four bells. To continue this documentation process, more intensive studies needed to be completed. On these categories, information was collected, but there is only partial information for each bell. Of the 157 bells documented, only 7 bells had documented photographs and audio data available to the public. Not only is the data incomplete, most of it is outdated as there have been many advancements in technology.

As for preservation conditions, 43 bells were given overall ratings dependent upon their outer shells. These ratings were based corrosion, cracks, and whether the bells could still be used. Only 14 of these 43 bells were deemed to be "good and usable" based on the opinions of the researchers. Data collection on specific bell parts was also uneven, with many details missing. For example, data for only 57 of the bells' clappers were recorded, and incidentally, only about a third were rated as being in good condition. Clearly, more data collection is needed,

[56]"Ufficio Stampa Comune Venezia."2014.

and what has been collected suggests preservation is needed. This data can be seen in Appendix I in graphical form.

2.3.1.2 Preservation Attempts have sometimes caused Further Damage

There are cases where attempts to preserve the towers that have made matters worse. In efforts to preserve or repair many old buildings, architects will often use newer materials to reinforce portions of the architecture. Unfortunately, this can have unforeseen and negative impacts, as Lagomarsino and others report. Reinforcing towers or old masonry with metal beams increases their susceptibility to earthquakes. Since steel and other metals are excellent conductors of seismic waves, adding these materials to the structures has the effect of amplifying any earthquakes and further damaging the structure.[57] In the case of bell towers specifically, the rotting wooden structures that support the bells and ringing mechanisms are sometimes replaced with metal, which transfers more of the vibrations to the masonry rather than allowing the wood to absorb the shock. Indeed, there are often attempts to harness new technology and transfer it to articles of the past. As researched by Klemenc et. al, older bells used cast iron or softer metals for the clappers, but the most readily available materials today are stainless steel and harder alloys. When the clappers in the bells were replaced with stainless steel, no problems were foreseen. Only after years of ringing was damage discovered: the harder stainless clappers severely deformed and wore the softer metal of the bell body, changing the acoustic characteristics of the bell.[58] These situations show that preservationists still have much to learn about preserving these delicate structures if they are to last for another thousand years.

2.3.1.3 Required Maintenance

Quickly forgotten are the bells hidden away in the towers above the city. Some are rung often, while others are incapable of ringing or are infrequently rung. Like any machinery, bells and the ringing mechanisms need careful attention and regular maintenance. All too often, the signs of such forgotten maintenance manifest themselves catastrophically and irreversibly. As

[57] Lagomarsino, Sergio et al. "Damage and vulnerability assessment of churches after the 2002 Molise, Italy, earthquake." 2004.
[58] Klemenc, Jernej et al."Dynamics of a clapper-to-bell impact." 2011-2012.

seen in this Figure 17, bolts holding the bells can seem acceptable from a cursory inspection, but only upon removal can the urgency of the situation be realized.

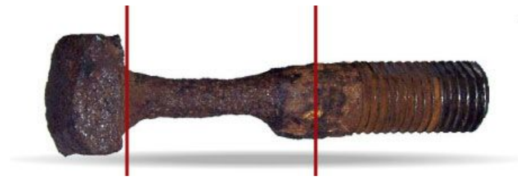

Figure 17: A rusted bell head bolt, likely to fail. Marked area indicates hidden part of bolt.[59]

While potentially catastrophic, this damage is easily repaired and the bells can be carefully preserved for years of trouble-free operation. Simply by inspecting the towers periodically, damage to the bell mechanisms can be seen before irreversible damage occurs. Some of the periodic maintenance includes inspection for rust and cracking of mechanisms, replacing rusted components, lubricating moving pieces and bearings, cleaning the bells of animal droppings, preventing ingress of small animals and birds, tightening loose bolts, examining wear of the clapper, and checking balance of the bell and clappers.[60] While an extensive list of steps, attending to these issues helps ensure expensive damage is avoided. Of particular concern are bird droppings, as they not only corrode metals when moisture is added, but they also provide a powerful disincentive for maintenance of the structures.[61] In Venice, this remains the case, as in the past, the Venice Project Center took nearly a dozen people a day to thoroughly clean out one bell tower of waste and prevent further incursion.[62]

With cleaning and maintenance sessions also come diagnostic tests and visits. By checking vibrations in the tower when the bell is rung, the state of the bell-to-yoke connection can be determined, as a bad connection will produce a sharp shock along the tower when the bell is rung.[63] In such cases as this, the bell ringing should be stopped. Additionally, automation systems have become a popular way to reduce the labor required to ring the bells, though the cost of automated bell ringing can be as high as €11.000.[64] It therefore remains imperative that the

[59] Verdin, Tim. “Verdin Bells & Clocks." 2011.
[60] Verdin, Tim. “Verdin Bells & Clocks." 2011.
[61] Corbett, John M."A Maintenance Checklist and Research Archive for Tower Bells." 2002.
[62]Carrera, Fabio. "IQP Team Meeting."2015.
[63] Corbett, John M."A Maintenance Checklist and Research Archive for Tower Bells." 2002.
[64] Corbett, John M."A Maintenance Checklist and Research Archive for Tower Bells." 2002.

bells and bell towers of Venice are vigorously inspected and maintained in order to preserve the structures and to ensure that Venice preserves its heritage for continued years to come.

2.4 Strategies for Advocating Funds for Bell Towers

Unfortunately, restoration is a difficult process to maintain without funding, as time and labor are limited. If there is public support for these structures, they can be preserved throughout time. Rabinowitz supports the traditional fundraising ideas of tax incentives, volunteer programs, implementation of historical committees, education, and advocacy.[65] Tax reductions, permit waivers, subsidies, grants and loans are efficient ways to gain support from the government, however the towers must meet certifications and regulations to qualify. In Italy, all property owned by the church is exempt from taxation, so all of the possible profits from donations will go directly to restoration efforts.[66] Community involvement through universities, volunteers, and small businesses is also known to stimulate small-scale support. Implementation of Venice Project Center efforts has drawn attention to the importance of the Venetian bell towers and is currently sparking the interests of the Association of Italian Campanology. As support grows, the next step would be to involve historical committees such as the United Nations Educational, Scientific, and Cultural Organization (UNESCO) and the World Heritage Convention (WHC). These organizations have been working together to promote intercultural appreciation through WHC sites to tie nations together by striving for common scientific gains, and finally to protect each cultures' diversity and their rights.[67] If a site has been deemed historical, as the city of Venice has, it is a time intensive-task to keep these treasures preserved due to an influx of tourists. However, with the funds that tourism provides, it is difficult to limit Venice to the public.

Public education and advocacy are key in gaining support for the Venetian bells and bell towers. Signs, posters, and social media can capture people's attention by displaying quick facts and illustrations of the bell inscriptions. A key example of this is the implementation of collection boxes strictly for the bell and towers. At Notre Dame in Paris, France, a collection box

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[65] Rabinowitz, Phil. "Section 7. Encouraging Historic Preservation."
[66] Toffolo, Piero. "IQP Team Meeting." 2015.
[67] "Introducing UNESCO." 2012.

is strictly dedicated to the preservation of its bells. Currently, they are in churches for preservation, but by creating one for the bells, Venetians and tourists will be able to visualize the importance of these icons. A more interactive way to gain support of possible donors would be the implementation of guided or self-guided tours. This idea is utilized by the Boston Freedom Trail, a trail through the Revolutionary landmarks of Boston. In addition to their guided tours, a foundation was created in order to preserve the trail's significance in society. From each tour ticket sold, one dollar is donated to the preservation fund for the Freedom Trail, and in the past year, $300,000 have been fundraised through ticket sales alone.[68] In addition, by accessing the foundation's website, the user can book a tour, make a donation, or enter the website store to purchase various items ranging from MP3 tour downloads to souvenirs. Although this organization uses the store to generate profit, this idea could be implemented in Venice to help raise preservation and restoration funds.

Currently, only the efforts put forward into preserving the towers and bells have been started by the Venice Project Center, but there have not been any strides to search for public support. In order to maintain these historical structures it is important to consider fundraising opportunities from third party sources. Promoting the advertisement of the bells and towers leads to future opportunities, and this was important when determining the scope of this project. The ultimate goal of VPC projects is for all the bells and bell towers to be put to better use, and unfortunately, without the funding or preservation of them, there will be no change from their current condition.

[68] Taylor, Suzanne. "Telephone Interview." 2015

3. Methodology

The goal of this project was to promote the preservation of the Venice bells and bell towers by publicizing their current conditions while also developing ways to renew interest. This was accomplished through the following four objectives:

1. Update and organize the current inventory of bell towers
2. Update and organize the current inventory of bells
3. Publicize information and develop a plan to allow for future updates
4. Create an outline for the long term preservation of the Venetian bells and bell towers

Seven weeks were allotted for the study in Venice, and fieldwork was limited to a five week period. The first week was spent obtaining permissions to study bell towers from the Church and the final weeks were needed for publishing the collected data and developing recommendations. To access the towers, we contacted Don Caputo from the Catholic Church, who obtained consent from the priests of each church to be visited. Throughout the study, the team collaborated with Pietro Salvadore, a Venetian campanologist who studies Modern Art and Bells, who helped organize the team's visits to the bell towers and analyzed collected audio data of the bells. In the sections to follow, the methods used to meet the project's objectives are explained and documented.

3.1 Inventorying and Organizing Information on Bells and Bell Towers

Beginning in 1995, the Venice Project Center partnered with the Earthwatch Organization to conduct tower surveys. Salvador organized the data sheets from this study by vicariate to facilitate future referencing. Our intention was to update and fill in the gaps in data collection. The team also met with Don Caputo at the beginning of the study, and he and his staff reviewed the list of towers the team wanted to visit. During this review, the church produced a new list which contained the official tower names that were owned by the church, totaling 98, and which could be accessed for the project. When the Earthwatch data was compared to this list of 98 towers, it was determined that there were, in total, 118 traditional campaniles and a velas in Venice.

As there were many aspects of the bell towers to capture, it was determined that two separate surveys could be used: an external survey and an internal survey. The external survey documented features of the bell tower visible from the outside. An internal or “ascended” survey captured the interior of the tower and the bells within. Initially, the team wanted to survey all 118 towers from the ground and complete as many interior surveys of the towers as possible. However, the great number of towers and time required to thoroughly survey them demanded that a different approach be taken. Thus, we focused on bell towers in the Vicariate of Cannaregio - Estuary, which includes two locations: the largest sestiere of Venice, Cannaregio (Figure 18), which contains 19 towers, and the northwest islands in the Venetian lagoon, where 12 towers were located. The islands visited included Murano, Burano, Mazzorbo, Torcello, Vignole, and Sant’Erasmo (Figure 19). Finally, before the scheduling was completed for the two main locations for the study, some ground surveys were conducted in San Polo (Figure 20), home to 10 towers, and test ascended surveys for the publicly accessible San Marco and San Giorgio towers (Figure 21).

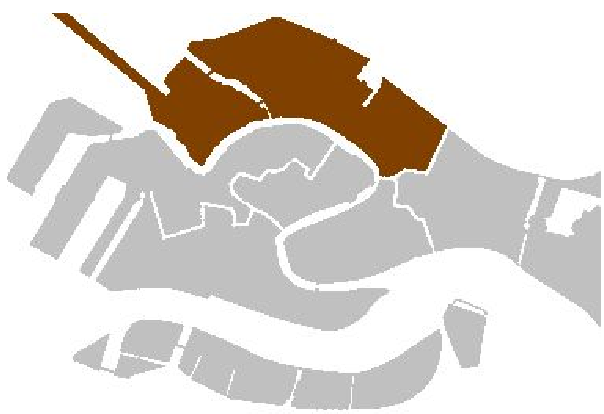

Figure 18: Location of Cannaregio in Venice.[69]

[69] Michiel1972.(sic) “Districts Venice - Cannaregio.PNG.”

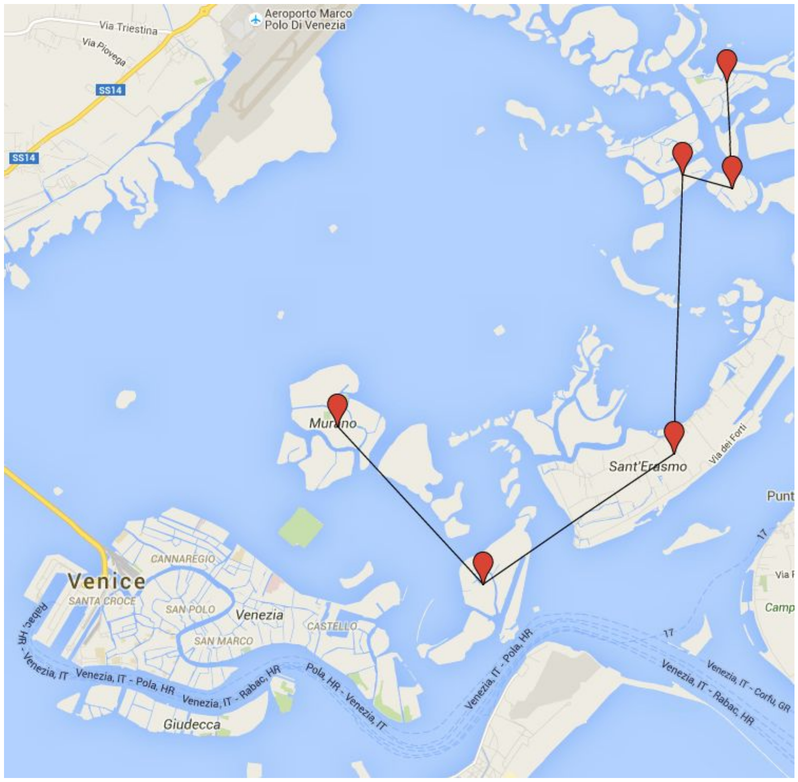

Figure 19: Northern Islands visited by team. Following the line from left to right: Murano, Vignole, Sant'Erasmo, Mazzorbo, Burano, and Torcello.[70]

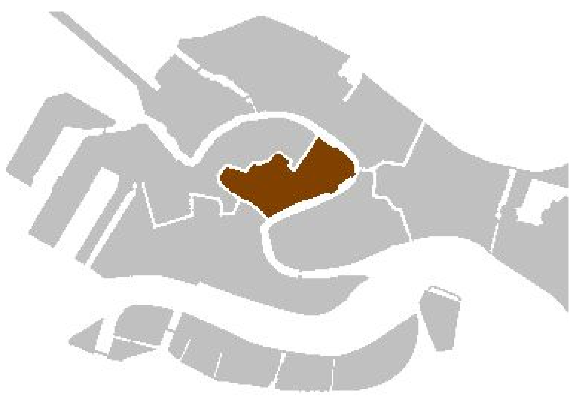

Figure 20: Location of San Polo in Venice.[71]

[70]"Venice, IT." Map. Google Maps. Google, 11 Dec 2015. Web. 11 Dec 2015.
[71] Michiel1972.(sic) "Districts Venice - san polo.PNG."

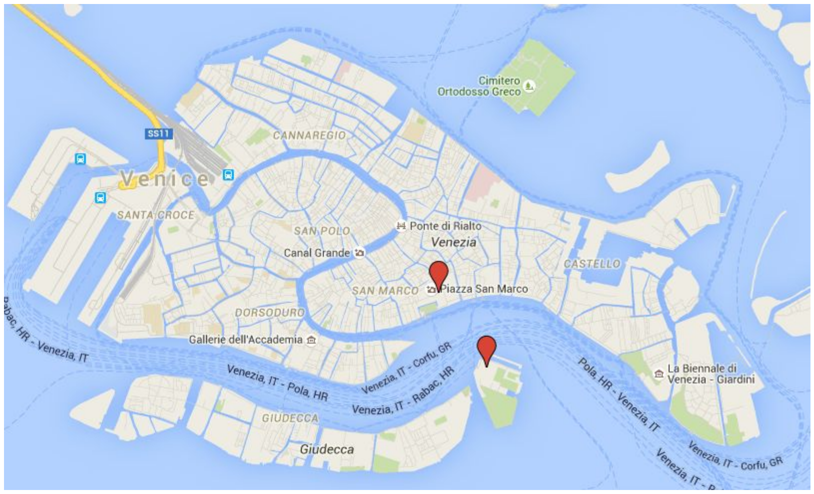

Figure 21: Location of San Marco and San Giorgio Bell Towers.[72]

Ascended surveys followed a schedule set by our collaborators, Salvador and Toffolo, who worked as liaisons for the team and coordinated with Don Caputo and the priests in charge of the bell towers to determine which were safe for the team to visit.. The team was accompanied by Toffolo and/or Salvadore during the ascended surveys since they were the point of contact with the church. In total, ascended surveys were conducted for 20 towers in these locations.

Details about the ground surveys and ascended surveys are explained in Sections 3.1.2 and 3.1.3 respectively. Data from the surveys was organized into a complex spreadsheet containing over 300 data fields. This information was helpful in assessing the overall condition of the structures and bells, and from this the team was able to determine the towers' and bells' accessibility, condition, safety, and need for restoration and preservation across the area investigated.

[72] "Venice, IT." Map. Google Maps. Google, 11 Dec 2015. Web. 11 Dec 2015.

3.1.2 Ground Surveys

Ground surveys were part of the cataloging process that took place on the exterior of the towers, intended to extract observable information about the tower from the outside. The goal was to ground survey eight towers. There were no restricting factors on this goal since permission was not needed to study them from the streets. Before departing on the data collection runs, it was important to have the following materials:

- Camera
- Meter stick
- Tape measure
- Notebook
- Pencil, paper, calculator

The philosophy with regards to data collection was to treat each tower as if it were being viewed for the last time and all pertinent observable and measurable data needed to be recorded for future reference. Each member of the team was given 30 of the cell columns printed on a piece of paper, t a reminder of what data fields were important for the spreadsheet. Key descriptions were recorded, including the material the tower is made of, locations (front, right, back and left) of visibility, if the tower was connected to other buildings and what side, details about the belfry including the drum style, arches, and finial, in addition to any art work, plants, cracks, holes, tie bands, windows, doors, clocks, and inscriptions were recorded in photographs using a camera. These data fields were immediately filled out into the master spreadsheet (Appendix D, E, F, and G), once the group returned from the field work. The master spreadsheet was broken into tabs labeled “Bell Tower Exterior”, “Bell Tower Interior”, “Bell Tower Extraneous Info”, and “Bell Info”.

In addition to these descriptions, we took measurements with a meter stick and tape measure depending up the availability of the tool between members or which device would be more beneficial. The foundation blocks were measured for height and width and occasionally depth if a corner of the tower was exposed. The door and window was also measured for height, width and depth using a measuring tape if they were reachable. All measurements were recorded on site in a notebook before being entered into the online spreadsheet.

In most cases the towers' height could not be measured directly because of physical constraints. For this reason height needed to be calculated through the use of trigonometry. By standing at a known distance from the tower, a triangle, as seen in Figure 22, can be formed using a person's head and line of sight as an angle and side of the triangle respectively. Using this generalization, a second triangle was formed using the same person's arm and a meter stick along the line of sight mentioned above and as seen in Figure 22. The meter stick was slowly raised until the top of the meter stick eclipsed the top of the tower. This forms a similar triangle with the same angle formed at the person's head as the larger triangle that uses the tower as its side. By taking the length of the meter stick used to form the second triangle and the length of observer's arm a ratio could be formed relating the two values. This is the ratio of length to height of the larger triangle as well as defined by the laws of trigonometry. By then multiplying the distance the person measuring is away from the tower by the ratio determined using a similar triangle, the tower height above the measures eyesight can be determined. The last step is to add the height of the observer to their eye level. The combined values are the total height of the tower.

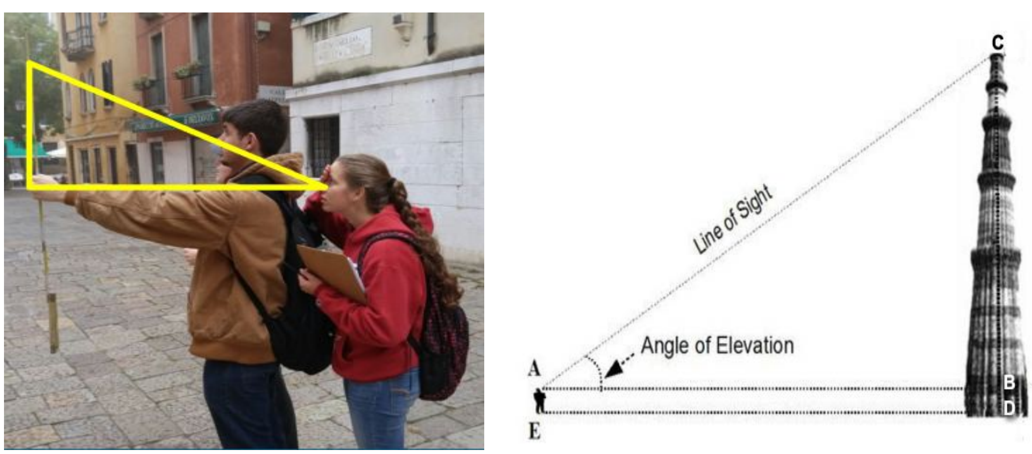

Figure 22: Creating triangle from observer to tower in determining height.[73]

[73] "FASCINATING FACTS OF MATHEMATICS."

Calculating Bell Tower Height:

Given X = distance from bell tower (Point E to D)

Given Y = Height of Tower above persons eyeline (Point B to C)

Given Theta = Angle of elevation from observer's eyes to Tower.

Given H = person's eye height (Points A to E)

Given T = Total tower height

Ratio = Meter stick length used in similar triangle / Length of arm to observer's eyes

Tan(Theta) = Y / X (The ratio explained above can be substituted in and replace (Tan(Theta))

Y= (tan(Theta) * X) (Rewritten can be viewed as Y = Ratio*X

T = Y + A

In most cases the distance to the tower was found by pacing off and calculating the length to the tower based on the observer's average pace size. Alternately, a Tango Tablet's "MeasureIt" application was used to approximate distances based on the device's position change in space between two points. If the distance to the tower was not physically possible to be measured due to a non straight path or other obstructions, a GPS estimation was used to find the distance to the tower from the observer's geotagged location. All other potential uses of trigonometry that were used during the surveying can be found in Appendix H.

3.1.3 Ascended Surveys

The ascended surveys were the portions of this project that involved entering the bell tower and ascending the interior. These surveys intended to provide detailed information about the condition of the tower structure and of the bells. This was done by recording and analyzing the sound of the bells with a Zoom H2 audio device, describing the bell dimensions by hand measurements, describing the hanging mechanisms, and recording inscriptions through photography. Photographs were taken of the interior of the tower as well and they needed to be thorough to cover the structure and damage of the tower. Captured places and objects included (if present):

- Entrance
- Ground floor room
- Staircases
- Landings

- Belfry
- Balcony
- Bells
- Bell support structures
- Bell ringing mechanisms
- Atic

Even if we had previous data from the VPC, we recollected it as a comparison because our technical equipment was superior in quality and likely to be more accurate. With the list of the data needed to be collected, the following checklist was completed for pre-departure:

- Collect the following materials:
    - Digital camera or camera phone
    - GoPro Hero 2
    - Selfie Stick
    - Zoom H2 or comparable audio recording device
    - Cellular phone
    - Video camera (or video-capable digital camera or camera phone)
    - Pencils and pens
    - Notebook
    - Specialty Equipment:
        - Handheld lighting
        - Project Tango Tablet
        - Chalk for highlighting inscriptions
    - Map of bell tower area
    - Meter stick or measuring tape
    - Personal Protective Equipment (PPE):
        - Ear plugs
        - Plastic gloves

        - Dust mask
        - Boots or plastic covers
    - Cleaning supplies for bells:
        - Sponges
        - Bucket of water
        - Mild detergent
        - Brushes
- Ensure sufficient memory space on electronic capturing devices
- Ensure batteries are charged on electronic devices

The team decided to divide the data fields from the master list among each member of the team so it would be collected more efficiently and smoothly. Before ascent into the tower, a member of the team was given the responsibility of taking care of the same data as described in the ground survey section above.

3.1.3.1 Shaft Surveying

A second person was in charge of documenting all of the details about the landings, starting from the ground entrance to the landing just before the belfry. Data included measurements of windows using a measuring tape, what side of the tower they were on (front, right, back, left), if they were blocked, barred, or meshed, any details about a clock mechanism if present in the tower, a 0-5 rating about the landing cleanliness, sturdiness as well as dimension, specific details about stairs and ramps including number between landings and their sizes, as well as interior and interior door dimensions. Documented in a notebook and photographs, visible cracks, holes and misaligned bricks in the tower were observed, taking note of the side of the tower the damage was located on. This was key information because it helps identify if there was any restoration from the past or if restoration should be recommended. A complete list of these data fields can be found in Appendix D, E, F, and G. Each of these data fields were chosen to help the group ultimately determine accessibility, safety, and condition of each tower in attempt to determine if the public would be able to ascend up into them or if an alternate use of the tower would be developed.

A GoPro video was taken during the ascent to provide viewers with a virtual first person experience of climbing the tower. In addition, we decided a 3D model of the space would provide a better understanding of the tower's structure and layout. A 3D data collection system developed by Google, called Project Tango, was used for this purpose. Using position tracking, depth sensing, and a color camera, a 3D color map of interior spaces and objects was created with Google's application, "Project Tango Constructor." The result of this mapping was referred to as a color mesh, which was a collection of colored polygons. An example of a color mesh created by this application is seen in Figure 23.

Figure 23: Rendered color mesh of the San Giovanni Grisostomo Bell Tower using Project Tango. View looking down into the shaft with staircases around the perimeter.

The Tango device was able to save the mesh in a number of ways. The first was automatically in a proprietary format to be reopened by the Tango tablet. The second was an open-source format for saving 3D objects, either a .obj or a .ply, both ways of encoding polygon coordinates and textures into a file as a coherent 3D model. Unfortunately, as seen by Figure 24, the models the Tango produced were rather rough. For this reason, traditional photographs were used to record the important aspects of the tower, and the 3D models served as supplements to the photographs.

Using a Project Tango Tablet, the Constructor app was started inside each tower with the intent of capturing the structure of the tower itself and the layout of the stairs and landings. If the interior was dark, a flashlight was used to provide uniform lighting as the app was running. The area needed to be thoroughly scanned, with the operator moving the Tango device smoothly as the color cloud points were collected. In essence, it was similar to taking a very detailed video of the space with the goal of covering each area of the structure. The stairs, belfry, ground floor, and attic were captured before stopping the collection. In very sunny environments, such as a belfry with large openings, the Tango Tablet was unable to capture point cloud information since the sun's infrared radiation overpowered the small dots the Tango projected. Therefore, the belfry was usually skipped with the Tango, and the quality of the capture meant using it on the bells did little more than provide a sense of bell positioning in the belfry and not preserve their inscriptions. An additional consideration was that when a particularly tall tower was entirely captured in detail with over twelve minutes of recording, the Tango failed to properly mesh the file, likely due to memory limitations of the device or thermal failure. Because of this issue, caution was taken during future scans: the mesh export was attempted before the team exited the tower, and if the export failed, the process was repeated either more quickly or with each landing being separately scanned to prevent data loss. The collected model was saved and also exported as a .ply. After the export completed, the model was visually inspected. Once the model was satisfactory, the software was closed and the device put into a sleep state until it cooled down.

3.1.3.2 Belfry Surveying

Another team member had the responsibility of documenting all details of the belfry. Once in the belfry, the architecture style, shape, finial (decorative element on the top of the tower), and balustrade (column like fence) observations were recorded through photographs as well as a notebook when necessary. Key measurements such as the length and width of the belfry interior was measured using a tape measure. Unfortunately an accurate measurement of the height was unable to be obtained, however an estimate was documented. The estimate was obtaining using google earth 3D pathing generator tool,selecting the area above the belfry to the top of the tower. Additionally, each window of the belfry was measured using a tape measure or meter stick to record the height, width, and depth. Specific to the belfry, a brick was also measured for its height, width, and depth. Observed descriptions of the frame were documented based on the shape, material, and current condition in addition to any cracks, holes, restoration or misaligned bricks. These data fields were important to analyze when determining the safety and condition of the tower, as an alternative use for these towers might be to hold small concerts in the squares during weekends or use them for tours. All recorded data was later documented into the master spreadsheet after returning from the tower, displayed in Appendixes D, E, F, and G.

One of the benefits that the bell towers provided was an excellent vantage point from which to observe the city of Venice. Since most of the towers are inaccessible to the public, many people have never seen the different views from around the city. Panoramas are a convenient way to collect this landscape information, and creating a 360-degree panorama allowed the full view from the tower to be captured, which was later placed on the website. There were several methods of doing this that were employed as situations provided opportunity: taking dozens of single photographs or taking one panorama from each side of the tower.

In the first case, photographs were taken from the balcony so that the city view from the tower was fully captured from each side. The camera remained vertical during the photographs to capture the buildings surrounding the tower, and each photograph overlapped about 25 to 35 percent of the frame with other photographs. If there was a mesh grate over the openings on the belfry, the phone was oriented between the mesh if possible. Later, these photographs were stitched together to form one 360-degree panorama. For the second case, most current mobile phones have built-in panorama capturing features, so these were employed in most situations where the windows were relatively large and the corners of the tower did not disrupt the view of the corner landscapes. Typically, one panorama was taken from a window on each side of the tower. The panorama mode was selected from the camera app, and the phone was directed such that an edge of the tower was just visible to the camera. The shutter button was pressed, and the phone was slowly rotated in place so that it would finally point at the other corner of the tower visible from that window. Once this was completed, the capturing was stopped, the panorama automatically stitched by the phone software, and the panorama was checked to confirm validity. Later, further panoramic software, the free Hugin software for PC, was later used to stitch those smaller panoramas to form the larger 360-degree one. As was often the case in the bell towers, the metal mesh or netting could not be moved from the window and posed a significant problem taking pictures of the view from the belfry. It was decided that the automatic panoramas could still be generated, and while they contained the netting, it was still better than not having a view at all.

When bells rang, they could, depending upon the type of frame mounting of the tower, generate large shocks and vibrations to the structure. It was important to check how much vibration the bell tower was subjected to from the ringing, as the mortar and brick of the building could easily become compromised over years of activity. One way to check how much vibration was transferred to the tower was by using an accelerometer to measure the accelerations of the tower while the bells were rung. If the bells rang on schedule during the survey, the vibrations were captured with the VibSensor app for Android. Smartphones usually include small accelerometers and gyroscopes in an Inertial Measurement Unit (IMU) package that can detect vibrations. VibSensor for Android was used and recorded measurements of vibrations caused by the ringing bells. The device was then placed on the floor of the belfry along an outer edge of the tower with the z-axis of the device facing upward, the x-axis pointing in the direction of the swinging motion of the bells, and the y-axis directed perpendicular to that motion. A short delay was used before collecting the accelerometer readings so that the user's movements were not captured and the device did not run out of memory. The data collection continued until the team returned to the belfry after the bells finished ringing to be sure that all resonations have been captured by the application. The results were then exported and saved as a comma separated file to be opened in Excel or Google Spreadsheets.

3.1.3.3 Bell Surveying

The diameter of each bell was taken by using a tape measure. Following a method taught by the campanology association partners, we did the following:

> Fix the end of the tape measure with the hooking tooth to the edge of the bell while keeping the tape measure under tension. After, extend the tape to the diametrically opposite end of the lip. For a proper fit, [we] need to scroll back and forth slightly, until it the maximum numerical value is recorded. The operation requires, normally, the manual movement of the clapper, therefore, can be useful, particularly in the case of a large bell, the help of a second person. To measure the diameter mouth, [it] requires the precision of a millimeter[74]

The diameter of the bell was a key measurement as the upper diameter, diagonal of the left, and inner height of the vessel could be calculated from it. All of these aspects determined the sound, and from them it was possible to calculate the weight of the bell since the bell casters followed specific rules for shaping and casting. However, it was useful to identify the nominal musical note from the bell geometry before the audio calculations took place because it allowed for data confirmation.

Another measurement taken from each bell when possible was the bell's thickness: the width of the bell wall at the location where the clapper hit the inside of the bell. At this exact point, the wall was at its thickest point. A special blacksmith's caliper was needed to document this data. The group was only able to complete this documentation when Matteo Padovani was present because it required experience to determine the exact location due to morphology changes over time.

The proportion of thickness to diameter was important when evaluating the bell shape. For example, a bell with a larger thickness will have a higher proportion because it is traditionally a fraction of one. Below is the equation to demonstrate the ratio.

$$\frac{S\,(mm)}{D\,(mm)} = \frac{thickness}{diameter} \simeq \frac{1}{14}(average\ ratio)$$ [75]

Additionally, the tape measure was used to measure the length of "skid marks" shiny markings where the clapper hits the side of the bell and sometimes "skids" across it. This data

74 Padovani, Matteo "Misurazioni Teccniche ed Elaborazioni Matematiche."
75 Padovani, Matteo "Misurazioni Teccniche ed Elaborazioni Matematiche."

was useful because gave an indication of the clapper's condition and we were able to determine if there was a safety concern when the bells ring.

Documentation of the condition of the belt and clapper were rated on a 0-5 scale. These two elements of a bell are extremely important because they are the mechanisms that work together to ring the bell and if there is a fault in either one, the swinging bell will be deemed unsafe and taken out of usage.

In order to record all information shown on the bells, the exterior and interior were taken photographed. Pictures or video were captured of the clapper, clapper support, and clapper strike points. Over fifty pictures were taken around the exterior. The intent was to have photographs covering every square inch of the exterior with significant cross-coverage. This was needed to later reconstruct accurate 3D representations fine enough for readable inscriptions. Each photograph overlapped about 25%, and approximately four different heights were used to capture each side of the bell fully, with ten to twelve different placements around the bell for those four vertical captures. This capturing method can be seen in a reconstruction of the picture locations seen in Figure 24.

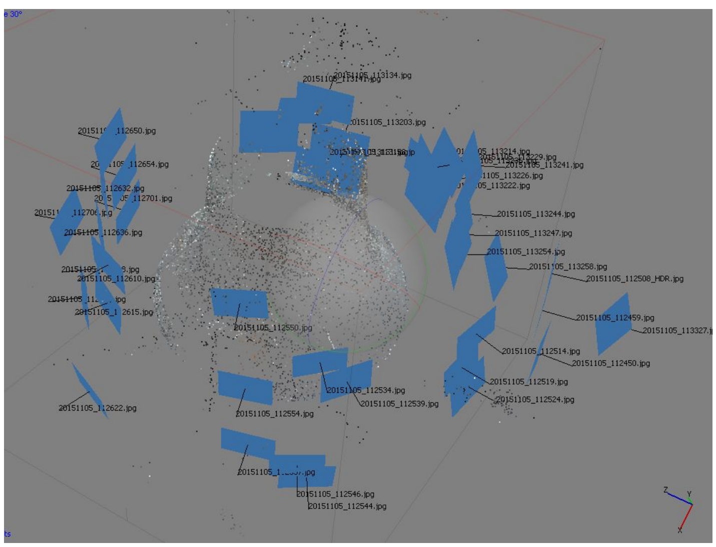

Figure 24: Reconstructed camera locations during bell photographing.

Audio recordings of the bells were captured using a studio-quality, stereo recording device, the Zoom H2,which could produce lossless audio in .wav file format. It was important to always record the bells since their purpose was to create music, and each bell has a unique sound recording a segment of Venetian history. If the team was present in the bell tower during a scheduled ringing, they used the Zoom to record the audio. However, due to the potential for hearing damage, this was done from the shaft of the bell tower. Regardless of whether the tower had a scheduled ringing, the team manually rang and recorded each bell in the tower by having one person lift the clapper and tap it against the bell wall quickly three to five times while another person held the Zoom around the center of the bell just below its mouth. Software, owned by campanologist Mateo, later determined the bell's musical quality and note. If the recording quality was doubted (i.e. background noise was present during the recording), this process was completed two or three times as needed to ensure a good recording was saved. If the clapper hit the bell too hard, the recorder was not able to record sound waves due to oversaturation of the amplifier, so a low gain was used on the microphone. It was extremely important for all personnel to be silent during these recordings, as the recorder was quite sensitive. Later, these recordings were uploaded so that the public could listen to the sounds the bells made and appreciate them.

3.2 Publicizing Information

Once the data was collected during the surveys and organized into a spreadsheet, it was placed into a database, processed into more web-friendly formats, and published on web applications so that the public could access it in an intuitive and thorough manner. Previous teams had already created means by which to publicize the information, mainly a wiki site, an online bells application, and a cartography site, so this project team expanded on those efforts. Each application will be discussed individually following Section 3.2.1 Data Processing.

The first means of publication was through Venipedia, a wiki sponsored by the Venice Project Center, which hosts articles and links about Venice. We updated and added different pages about the bell towers and bells of Venice. Venipedia contained textual and photographic information about the towers and bells, as will be shown in Section 3.2.2.

The online bells application is located at bells.veniceprojectcenter.org. It displayed previously visited bell towers on a map, which, when clicked, navigates the user to a page displaying interactive information about the tower. This application was modified as explained in 3.2.3.

Finally, the cartography application displayed the outlines, names, and Venipedia links of bell towers in several historic maps created between 1500 and 1900. The team updated each application during the study in Venice.

3.2.1 Data Processing

The content of both Venipedia and the bells application was generated from the VPC's data repository, also referred to as the City Knowledge (CK) database. Before the data could be published, some of it had to be processed into a form that was more conducive to upload onto a database for online sharing and viewing. Such data included audio recordings, seismographic data, photographs, and 3D models captured with the Project Tango.

When placing audio files on the Internet, it became important to choose formats which functioned well for devices with slower data speeds, such as mobile phones. While the Zoom device recorded at very high quality, lossless audio, those files had to be compressed into the popular mp3 file format. This allowed audio to be played quickly over the web with little loss of quality. It also prevented the application from consuming large portions of a mobile data plan if someone chose to view the content on their phone. Additionally, any silences in the audio samples were trimmed out so that the file contained only useful information. Using a computer program such as Audacity, the sound recordings of the bells were trimmed such that the file nearly immediately played the sounds of the ringing bells and the result was exported as an mp3 file. For each bell, there was at least three distinct rings before the audio was cut. The end of the file was also terminated before background noise became more audible than the sound of the bell, and the audio was modified so that the end of the file faded into silence. Bell towers which had multiple bells or precise patterns of ringing also had a separate file of that ringing recorded to demonstrate how the bells would normally sound to an onlooker. Once the trimming and exporting was complete, the audio was ready to be uploaded into the CK database.

Google Photos, an online photo sharing and storing service, automatically created panoramas of images uploaded together after about five minutes. The photos taken from the belfry of the surrounding view, as well as the other photographs for safe keeping, were uploaded to Google Photos. After five to ten minutes, longer for very large batch uploads, the team verified whether Google Photos was able to automatically create the panorama. If the disparity between the images was too great for Google Photos to understand, a separate panorama application, such as the open source Hugin software, was used to create panoramas from the captured photographs. In this application, the photographs were loaded into the program after having the visible portions of the tower, such as columns, cropped out of the photographs. The lense data for the camera was entered for each picture as it was loaded, and the alignment procedure was started. This attempted to connect features in each image to the same features in other and position those photographs next to each other. Once the software aligned all the photographs, the dimensions of the panorama were adjusted such that a full 360 degree shot was created. Then the software stitched the photographs together to generate the final result, which was saved as both a Portable Network Graphic (.png) and a compressed .jpeg for use online.

From the application VibSensor, a comma separated file (.csv) readable by Microsoft Excel was created with the seismic data recorded during the bell tower ringing. Since an Excel table was not a convenient way to visualize the vibration data on the Internet, a graphic would be created so that a user could quickly glance at the graph and understand how severe the vibrations were rather than scroll through several thousand rows of Excel values. The csv was then opened in Excel and and a combo chart was created which displayed each axis vibration over the time on one line graph. Finally, the data were trimmed sufficiently by hiding rows so that the graph showed the most amount of activity possible with a brief period of no activity before it. This graph was then exported as an image to be uploaded to the server. After conducting a sample seismic data test, Figure 25, was created from the vibrational information.

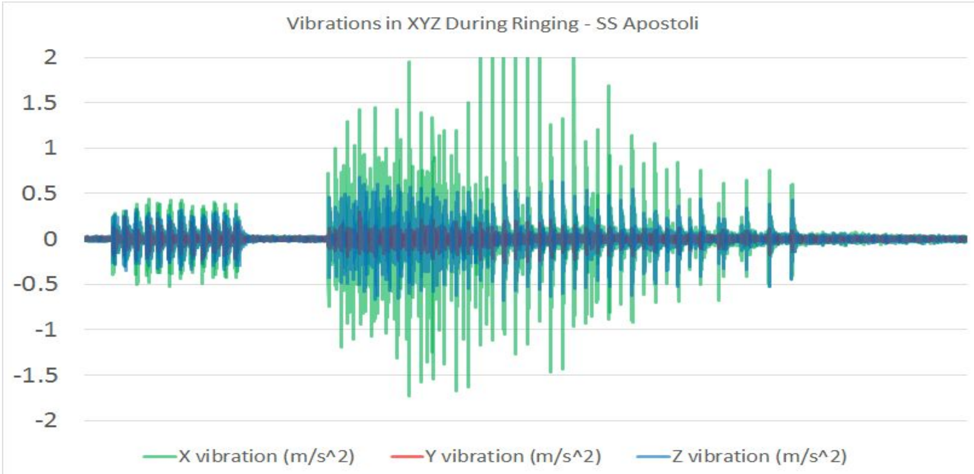

Figure 25: XYZ Vibrations caused by ringing the bells in SS Apostoli. First group of shocks due to hammering the bell, second group caused by swinging.

Since it was difficult to store, review, and conceptualize many photographs taken of a single bell, the team decided to use an alternative method for presenting photographs of a single object, in this case, a bell. Since it was quite common for consumer devices to be displayed as 3D models that could be rotated, zoomed, and interacted with, the team decided to do the same for the bells as it would provide an interactive user experience and fully preserve the bells in three dimensional imagery. This approach also had the benefit of compacting the hundreds of photographs captured of the bells into a single file which was able to be uploaded and described by a single URL.

It was possible to construct 3D models using photography alone in a process known as photogrammetry. Using Agisoft's PhotoScan, the pictures taken of each bell were individually analyzed to create a 3D model of the bell, and a similar process was used to create a model of the belfry. This process involved five steps. The first was to import the photos and, if the subject was a bell, mask the background. Masking allowed the software to ignore background features so a more accurate model can be created of just the bell. Secondly, the cameras were aligned, meaning that the location of each camera was determined by finding common elements in the photographs. Figure 26 displays the result of this alignment:

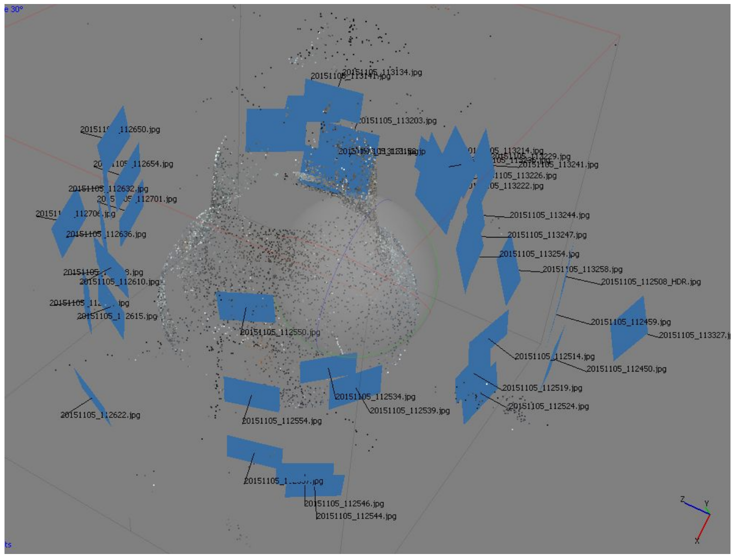

Figure 26: Reassembled camera locations

In the third set, a dense point point cloud was created where the software used the determined locations of each photograph to draw more points of intersection from each photograph. The dense point cloud is seen below in Figure 27:

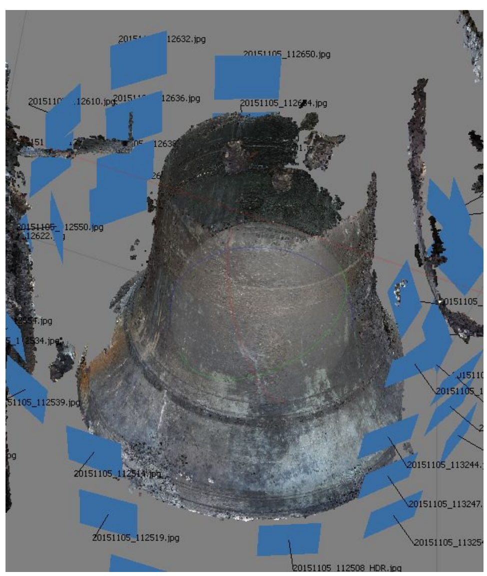

Figure 27: Assembled dense point cloud of a bell

Fourthly, a mesh was created between the points, which allowed for a model to be created with much fewer data points in the file and texture to be added. Finally, a texture was overlaid on top of the mesh with the information collected from the cameras. Figure 28 shows the final textured model of a bell

Figure 28: Textured model of a bell created with PhotoScan

Once the cloud point data was collected for both the Tango and the bells using PhotoScan, Sketchfab, an online 3D model sharing website, was used to upload and save the 3D models. The Tango's .ply collected from the bell tower was first downloaded onto a computer. The file was then appropriately named according to the bell tower in which it was captured, and the web interface for Sketchfab was used to begin the file upload. Similarly, from within PhotoScan the textured model was directly uploaded to Sketchfab. Once the file was fully uploaded and rendered, the integrity needed to be checked, and then the link was saved for that particular bell or bell tower. The model, located on Sketchfab, could then be accessed anywhere on the Internet and embedded into the Bells Application. Model URL links were then uploaded onto the CK database.

Once the above four preprocessing tasks were completed, work was started on publicizing the data. These application and site modifications are explained in further detail below.

3.2.1 Venipedia

Venipedia was able to display photographs and textual information about the bells and bell towers, but for security purposes it was unable to display the interactive media that could allow a malicious user to embed in inappropriate content. Thus, the team was limited in the changes and additions it could make to Venipedia.

Bells and bell towers were discussed in Venipedia in two ways. The first was through four general articles which cover general information on bells and bell towers (“Bell” and “Bell Tower”); and Venice-specific facts and summaries of bells and bell towers in Venice (“Bells” and “Bell Towers”). An example of one of these pages, the Bells page, is shown in Figure 29 while all of the pages can be viewed in Appendix J. These four articles were created by hand, meaning that people created the articles and typed the source text directly into the wiki and saved it.

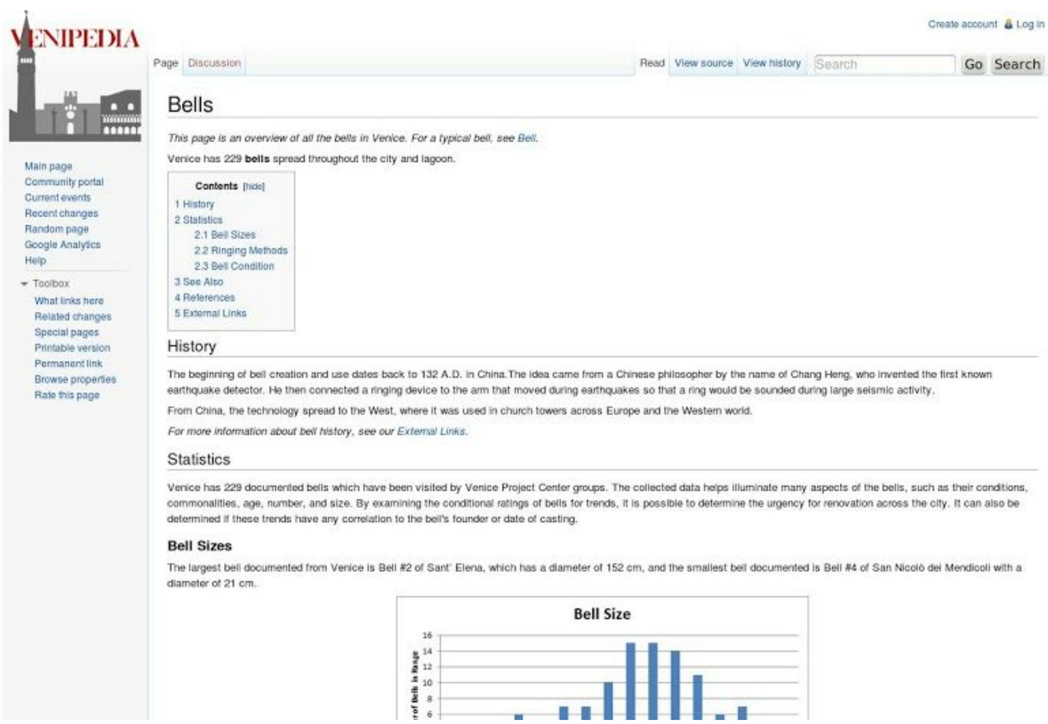

Figure 29: Example of Bells of Venice page in Venipedia

The second method bells and bell towers were discussed in Venipedia was through the automatically generated articles of every bell and bell tower in Venice and the lagoon. These articles did not have modifiable source text contained in the wiki, so they could not be modified from Venipedia itself. Rather, they were generated from templates and data saved within the CK database. To change those articles, modification of the data on the CK console was necessary. An example of this type of article is seen in Figure 30.

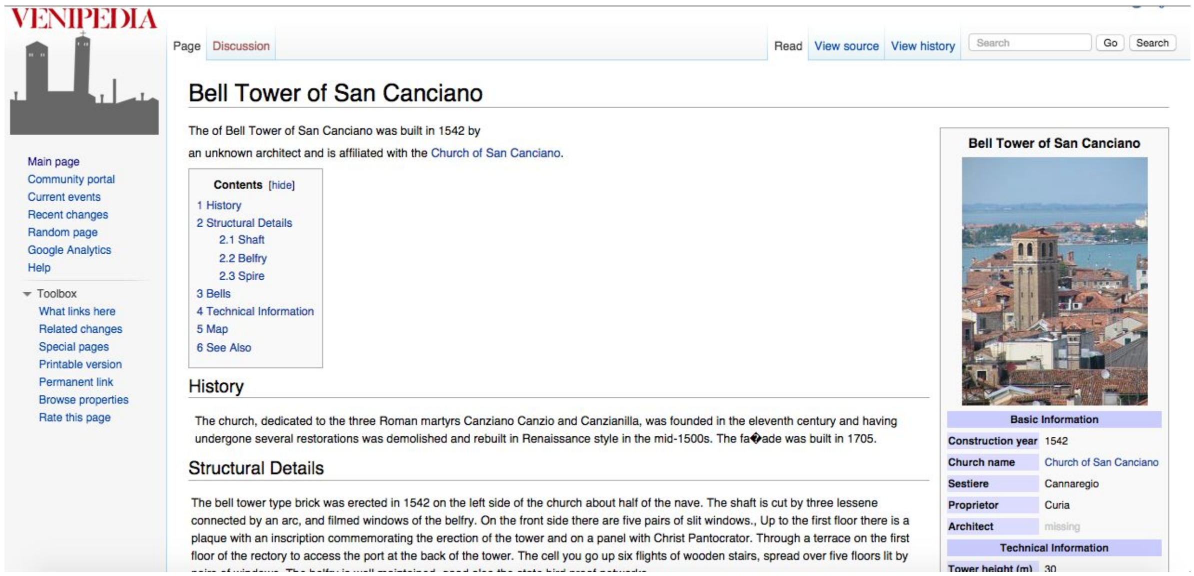

Figure 30: Example of Bell Tower page in Venipedia

Changes made to the general bell and bell tower pages on Venipedia included grammatical corrections and improvements, media updates (when better pictures were available), and content additions. Each team member was responsible for updating one of these general pages and created the revised pages. Based on the new research that was conducted, the articles were also expanded with new resources and information captured during this project.

The pages generated automatically for each bell and bell tower in the CK database were revised by modifying the templates and regenerating the pages. A problem with all of the automatically generated pages was that images could not be clicked on to view a full resolution copy. This meant that often the only picture of the bell tower was a low quality thumbnail image, and panoramas were reduced to the size of about one by three inches. Since the photographs were stored on the database and included original, small, medium, and large sizes of each image, the template was simply modified to hyperlink each preexisting picture to the original such that a user could then click on an image to see a full size. The templates were also modified to reduce the number of times the word “unknown” appeared on the page. Previously, whenever the template attempted to gather a piece of data from the database that did not exist for that tower, it would simply insert an “unknown” string instead. This was alleviated somewhat by manipulating the template to cease from printing the label for the information if no data was present.

3.2.2 Bells Application

Since Venipedia contained the textual information about the bells and bell towers with few photographs, the Bells Application was created by past groups to display more interactive forms of data such as panoramas and audio in an engaging way. The home page of this website, seen in Figure 31, displays an interactive map with pins to identify where the bell towers are within Venice and its surrounding islands.

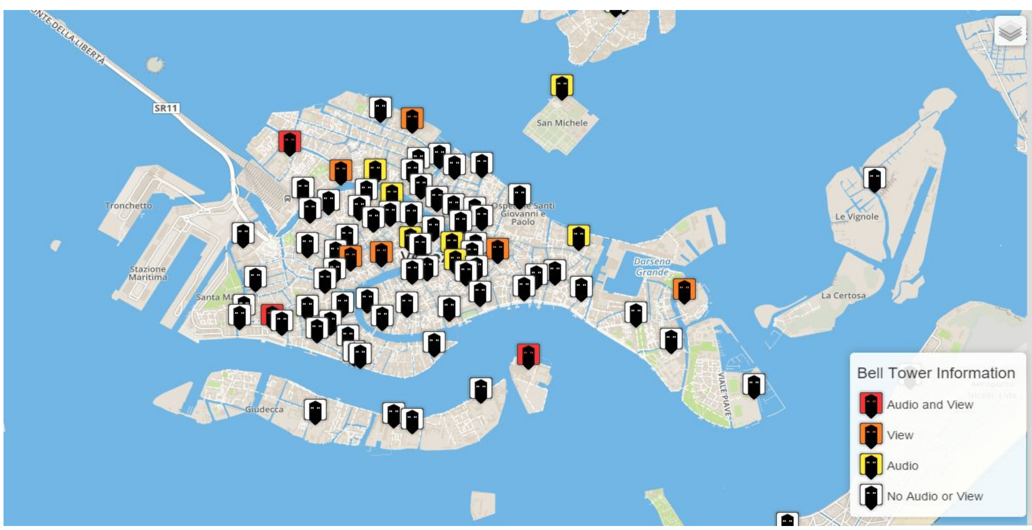

Figure 31: Online Bells Application home page before changes from this Project

Previously, the various color pins on this map represented the ones with both audio and views, just views, just audio, and no audio and views. By clicking on a specific bell tower on this map, as seen in Figure 32, the viewer was able to read quick facts about the tower, hear the sound of bells ringing within that tower, navigate to the Venipedia page, and go to a page with more information.

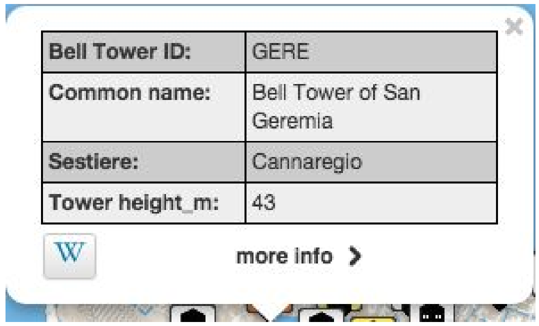

Figure 32: Sample pop-up menu for the San Geremia Bell Tower

We imported new bells and bell tower data, documented status, and added 3D data, video, and audio for each bell. The pins and coloring system were reformatted used to show completeness of data to better illustrate missing data and the bell towers' condition, safety, and accessibility.

To show the 3D data collected for the bell towers, the CK database was modified so that each bell tower entry could also contain URL's to the video of the tower ascent and to the 3D models of the belfry, shaft, and bells (when present). With this data saved, the bells application's more info page template was modified to embed the models hosted by Sketchfab as well as the YouTube video of the tower ascent.

The bells audio addition to this application was inspired by the VeniceBells.com website, which had a page of each bell tower's bells. Each bell could be clicked to hear the sound of that particular bell, so in the more info page of the improved online Bells Application, a hyperlink was included below the 3D bell model that, when clicked, played the sound of the bell for the user. The chorus, symphony, or timed ringing of the tower's bells remained able to be played from the pop-up menu located on the main home page/map. VeniceBells.com's other feature, allowing a user to listen to the bells across Venice at a specific time of day, was deemed too extensive to incorporate into the existing Bells Application without significant modification. Thus, the project group focused on adding the individual bell sounds to the more info page of the bells application, resulting in a website that was much more organized, interactive, and user friendly.

3.2.3 Cartography Application

The application used to display six archaic maps of Venice, known as the Cartography Application located at cartography.veniceproject.org, functioned by storing a number of layers for each cartographic map that could be toggled to highlight different points of interest. A layer contained polygons that were drawn on the map for specific points of interest, such as islands or churches. For this project, the layer entitled Bell Towers was updated and modified. This layer highlighted and named the bell towers seen in a map, as demonstrated in Figure 33, which made the bell towers easily identifiable in the map.

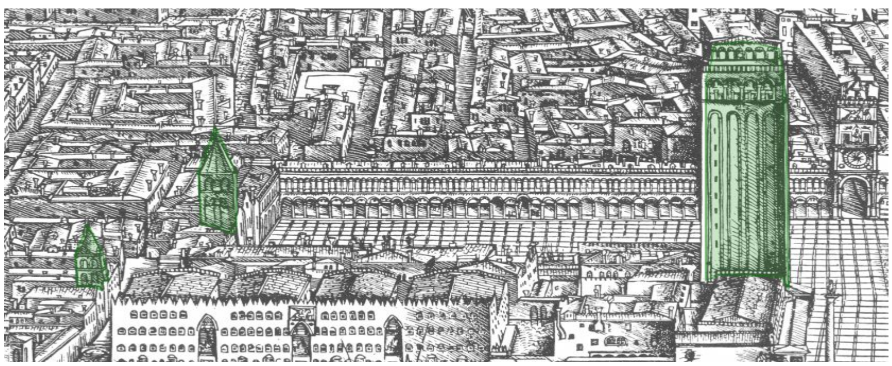

Figure 33: Highlighted towers in the Cartography Application

In addition, clicking on the highlighted tower produced its name and a link to that tower's Venipedia page, though some of the previously produced names were generic, such as Bell Tower 34. Only the first map from 1525 A.D. contained highlights, and of the roughly 100 bell towers highlighted in this map, only 24 were named. Even fewer were linked to the Venipedia page for that bell tower. The team was responsible for naming the unnamed bell towers in the first map and adding the bell towers in the five other more recent maps. Finally, the students added the bell towers to the other maps by drawing polygons around each tower and selecting its name from the objects included in the Bell Towers layer.

3.3 Long Term Preservation

To maintain and preserve Venice's bell towers and bells, public support is needed. A plan was devised to raise interest and funding in the bell towers and several possible ideas were researched by the group. We organized our ideas around four main strategies for preserving historical sites. These concepts of public support included call to action, historical committee assistance, merchandise development and alternative uses of bell towers[76]. We researched and compared previous efforts in other cities such as Paris, France, which promotes preservation through church donation boxes and miniature replicas of historical buildings in the form of keychains, t-shirts, and music boxes. Similarly, in Boston, Massachusetts, the group learned about preservation through the Boston Freedom Trail's public tours, as stated above. Other examples of long term preservation we discovered include ideas for alternative use such as a sprinkler system, an All-Sky camera, tower concerts, and tower observatories. Another observed example was from Munich, Germany. A bell tower located in Marienplatz, a well - visited tourist destination, has been converted to a tower observatory where viewers can experience a 360 degree view first hand of the city for a small fee.

Once we researched what other historical preservations groups had done, we determined which ideas might be feasible to reproduce in Venetian bell towers. A pros and cons list was created based on our experience in Venice for each feasible idea in order to guide the development of merchandise in addition to implementation of alternative uses for the towers. Then we were able to develop three of our ideas to further pursue and create long term recommendations for the rest with hopes that future VPC efforts will be explored.

[76] Rabinowitz, Phil. "Section 7. Encouraging Historic Preservation."

4. Results and Analysis

During the period of November 5th to December 6th, the Bellvue Team was granted access to the towers in the Vicariate of Cannaregio-Estuary, where the team ascended 20 bell towers and conducted surveys. In this Vicariate, specifically within the sestiere of Cannaregio, we gathered data internally and externally from the 12 bell towers shown in Figure 34:

- Sant'Alvise
- Santi Apostoli
- San Canciano
- San Felice
- Santa Fosca
- San Geremia
- San Giobbe
- San Giovanni Grisostomo
- Santa Maria dei Miracoli
- La Madonna dell'Orto
- Santa Maria di Nazareth Gli Scalzi
- Santa Sofia

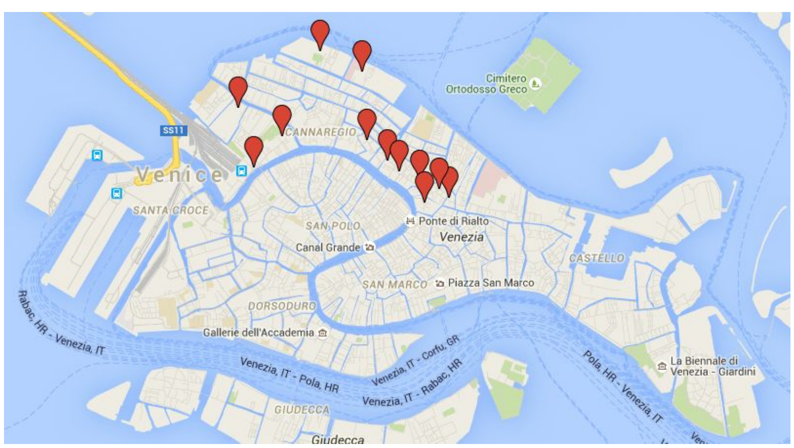

Figure 34: Location of Cannaregio bell towers[77]

[77] "Venice, IT." Map. Google Maps. Google, 11 Dec 2015. Web. 11 Dec 2015.

Another eight bell towers within the Vicariate were visited on the northwest islands (Estuary) of the Venice lagoon, Figure 35:

- San Martino
- San Angelo
- Santa Caterina e San Pietro
- Santa Maria degli Angeli
- San Donato Martire
- San Pietro Martire
- Sant'Erasmo
- Santa Maria Assunta

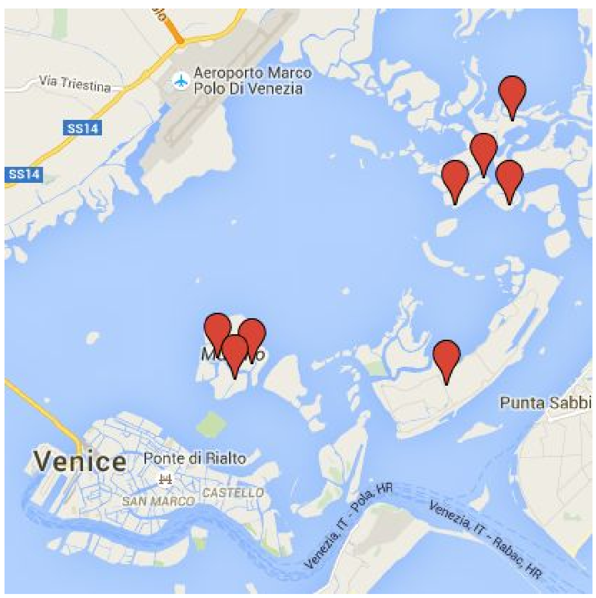

Figure 35: Location of northern island bell towers in the lagoon[78]

Although not in our initial plan, we also conducted two ascended surveys of San Marco and San Giorgio, located in Figure 36. Because they were the only two open to the public in

[78] "Venice, IT." Map. Google Maps. Google, 11 Dec 2015. Web. 11 Dec 2015.

Venice and we could access them easily, we visited these to test our methods before conducting the aforementioned ascended surveys.

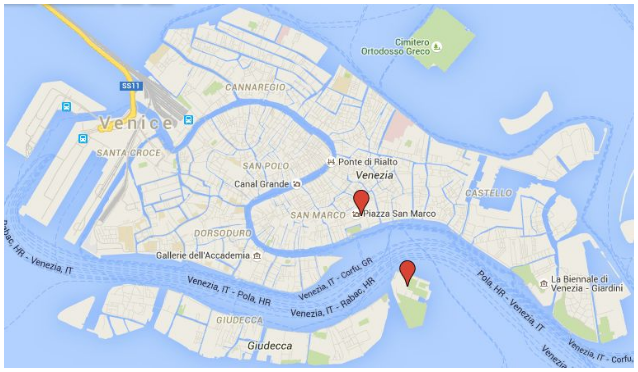

Figure 36: Location of San Marco and San Giorgio bell towers[79]

In the sestiere of San Polo, the following 8 bell towers were documented in ground surveys. San Polo was chosen because there were a small number of towers within close range to one another. We decided to conduct external surveys here to assist in the data collection for future teams so they could focus on the internal surveys of these towers, Figure 37:

- Sant'Aponal
- San Cassian
- San Giovanni Elemosinario
- Santa Maria Gloriosa dei Frari
- San Giacomo Apostolo
- San Paolo Apostle
- San Silvestro
- San Tommaso Apostolo

[79] "Venice, IT." Map. Google Maps. Google, 11 Dec 2015. Web. 11 Dec 2015.

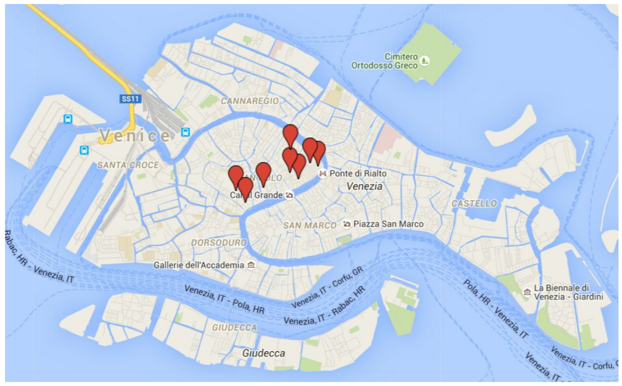

Figure 37: Location of San Polo bell towers[80]

4.1 Analysis of Updated Inventory of Bell Towers and Bells

Each bell tower and their respective bells contained a wide variety of data fields, both quantitative and qualitative, that we used to analyze safety and accessibility. With these categories in mind, we also documented our individual impressions of each tower.

4.1.1 Key Features of Bell Towers

In the lagoon, we observed 20 of the 107 campanile a torres and did not visit any of the 11 campanile a velas. The first measurement that was taken from each tower was its height. Heights ranged from 8 to 100 meters; the most common height was 24 meters and average tower height was 39 meters as depicted in Figure 38.

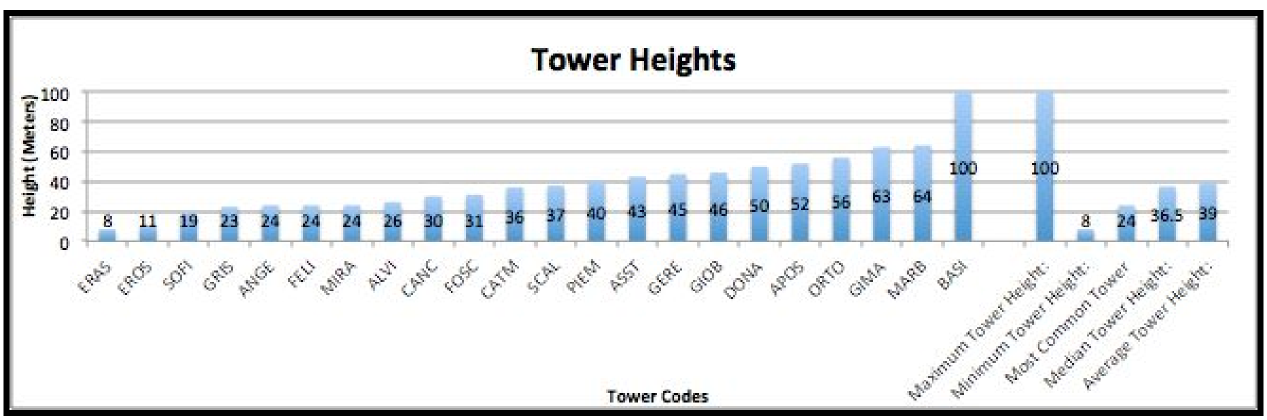

Figure 38: 22 ascended tower heights in meters

[80] "Venice, IT." Map. Google Maps. Google, 11 Dec 2015. Web. 11 Dec 2015.

Additional data gathered included the type of walkway to the top of the belfry in each tower. We discovered that 17 out of the 20 towers surveyed had a combination of stairs, landings, and ladders leading into the belfry. Of these 17 bell towers, the average number of steps in the bell tower was 124 steps. The remaining three bell towers, La Madonna dell'Orto, Santa Maria Assunta, and I Santi Apostoli used a ramp system to reach the belfry. Of the 17 towers with stairways, I Miracoli and Gli Scalzi contained spiral staircases with no breaks between the base of the tower and the belfry.

From the 20 bell towers visited, 12 had an A-frame while the remaining 8 were supported by parallel H-frame mountings. Both the A-frames and H-frames were made of either wood or were renovated with metal. Of the frames surveyed, eight were made of wood with the remaining 12 being made of metal. Within the belfrys, the size and number of windows was recorded. On average, the number of windows found within the belfry was 12, meaning there were three on each side of the tower. The windows averaged 224 cm high by 99 cm wide. It was also found that 17 out of 20 of the towers visited had mesh coverings over the windows. The sizes of each belfry were measured as well, resulting in an average floor area of 10.25 square meters, approximately 3.2 meters long by 3.2 meters wide. In many of the towers' belfries, the brickwork had been plastered over, augmented with metal supports, or simply replaced with new masonry. It was documented that there were visible repairs contrasting the original work in approximately 45% of the belfrys. This is excluding any repairs that completely masked the original stone or metal work, potentially hiding any restorations.

4.1.2 Key Features of Bells

Within the belfrys, the bells provided an abundance of data to record. Similar to the heights of the tower, the bell diameters were a very distinguishable characteristic of the bells. These measurements are plotted in Figure 39. The bell diameters were usually different from each other and there were not many similarities, so to display this data a range of five centimeters was used as the x axis interval to create a histogram of the data.

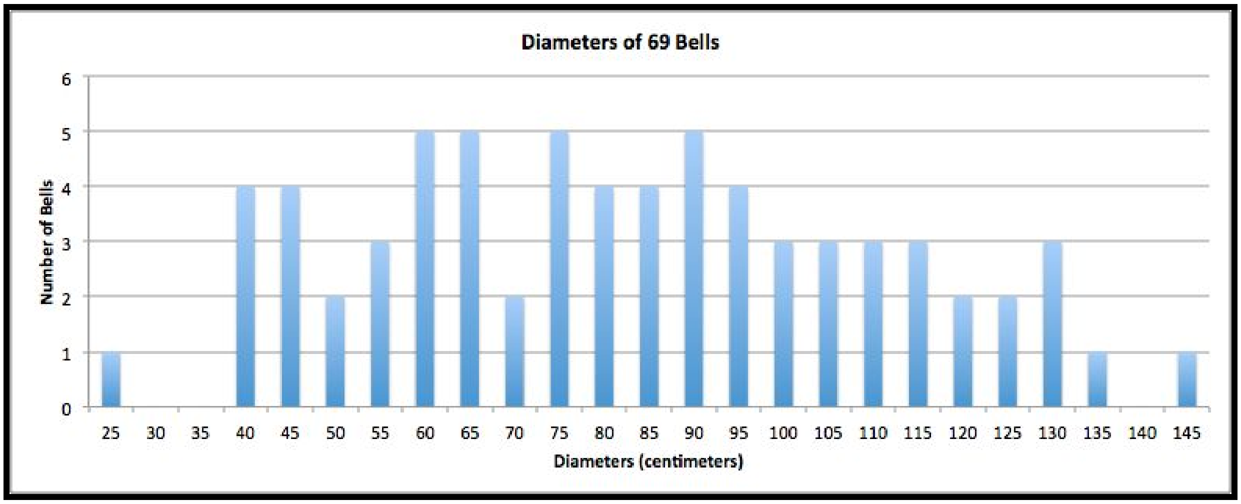

Figure 39: Diameters of 69 bells

Less important to the bells' sound, but still relevant to their conditions, was their internal height and skid mark lengths. Those values found during the surveys were 82 cm for internal height and an average skid mark of 5.2 cm. The skid marks were recorded from the center of the striking area, meaning a skid of 5.2 cm creates about a 10 cm skid mark on each side of the clapper strike point. Additionally, it was found that each belfry contained, on average, 4 bells. These bells hung an average of 160 cm off the ground, meaning less than half the population could stand under the average bell. The last observed characteristic of the bells was their inscriptions. Bells were found to average approximately two full inscriptions per bell with an average of 4 pieces of artwork, excluding the trimmings along the crown and lip of the bells. In addition, approximately six bells had major restorations completed or were simply replaced as a whole. While many of the bells did not have visible restorations, some were in a state where restorations were needed. At least 50% of the bells had instances of rust, chips along the lip, or large and developed skid marks.

The most important data collected from the bells were the sounds. We were able to collaborate with Salvadore and the Campanologist Association of Italy to use software called Wavanal to evaluate the bells' nominal notes and an assortment of tones. Although all sound data was collected, this analysis could not be completed for all 69 bells visited during this project span. Table 1 represents the only individual analysis gathered from the five bells of SS. Apostoli.

Of this plenum of bells, Bell 2 is shown in red because it is out of tune and of poor sound quality due to lack of preservation or poor casting.

BELL	I	II	III	IV	V
NOMINAL - STRIKING NOTE	**b/1 +45**	**d/1 -15**	**eb/1 +20**	**db/2 -35**	**e/2 +45**
SHAPE	Octave	Octave	Octave	Septime	Octave
GROUND TONE	B/0 +35	D/0 -21	Eb/0 +32	Db/1 +14	e/1 +1
PRIME	B/1 +35	d/1 -71	eb/1 -17	db/2 (?)	e/2 +59
THIRD	d/1 +48	f/1 -26	gb/1 +23	e/2 -47	g/2 +61
QUINT	gb/1 +4	a/1 -109	Bb/1 -8	ab/2 +27	b/2 -33
UPPER OCTAVE	b/2 +43	d/2 -14	eb/2 +20	db/3 -37	e/3 +44
Ø in cm	141,6	125,4	116,0	69,5	54,9
THICKNESS IN CM	9,8	8,8	8,1	5,0	4,0
KG	1660	1140	910	195	100
VIBRATION / SEC					
Crown / -	Crown	Crown	Crown	Crown	Crown
Caster	Colbachini	Colbachini	Colbachini		
Place	Bassano	Padova	Bassano		
Year	1853	1980	1853		
ringing system	Slancio - Flying Clapper	Slancio - Flying Clapper	Slancio - Flying Clapper	Slancio - Flying Clapper	Slancio - Flying Clapper

Table 1: Analysis of Bell Sounds from SS. Apostoli

4.1.3 Safety of the Bell Towers

Safety was determined in terms of the amount of observable structural damages. These warning signs of collapse included how much a tower was leaning, the quantity of cracks or holes, the sturdiness of the structure, severity of vibrations, frame material, or anything that could cause the tower to collapse. Before ascending into each tower, it was important to note any structural observations from the exterior such as cracks in the foundation, tie bands running along the outside of the shaft, or whether the tower was leaning towards one direction. Likewise, for the interior, cracks, holes, damaged bricks, and the structural components of the landings were also documented. In all 20 towers examined, there were minor restoration efforts to combat or document a potential risk of collapsing such as the implementation of tie bands or stress gauges to monitor cracks.

Observed with the naked eye, 3 of the 20 towers were significantly leaning in one direction. The following towers to monitor are Santa Maria degli Angeli, San Martino, and Santa Caterina e San Pietro. Although we were unable to determine the angle at which they were leaning or the integrity of the structure, future observations and measurements should be made using a pendulum device to measure the tilt of the tower to determine the tower's safety. This would account for tilting dangers not only associated with ascending the tower, but also with the surrounding churches, homes, and businesses.

Among the 20 surveyed bell towers, there was an average of 17 cracks or holes. The tower with the most cracks and holes was San Geremia with 114. This data is accurate because other groups have visited this tower in the past and it has 14 landings, the most of any tower visited. San Giovanni Grisostomo had the least number of cracks and holes with 0. Cracks and holes were most common on the right side of the tower (95 in total from the 20 towers). This may correlate with the direction in which the bells swing, as over 60% of bells swing right to left. We were not able to determine if this data directly correlated to determining a tower's structural integrity because cracks varied in size, ranging from only a couple of centimeters to over 30 centimeters as seen in Figures 40.1 and 40.2. Holes have diameters ranging from one to six centimeters. At the time of our data collection, we did not record the size of the cracks or holes, only the total quantity per wall on each landing. This was because we based our data collection off of the 2012 and 2013 bell tower projects conducted by the VPC. They did not suggest any specific changes to the data collected, thus we did not adjust the spreadsheet characteristics as listed in Appendices D, E, F, and G.

Figure 40.1: Crack in La Madonna Dell'Orto longer than a person

Figure 40.2: Crack in Sant'Alvise only a few centimeters

In addition to the documentation of cracks and holes, it was important to note any damaged and misaligned bricks on each wall of the towers. A brick was deemed damaged if there was any crumbling at the corners or if they were clearly misshapen compared to the other bricks in that tower. Approximately 14 bricks per tower were damaged or misaligned, but there were not any significantly degraded bricks. San Geremia had 116 bricks that were not in their original conditions, and Santi Apostoli only had 3 damaged bricks.

Tie bands were documented similarly to the way cracks and holes were, by each landing and side of the tower. From the 20 towers examined, there was an average of 11 tie bands per tower. Bell tower of San Donato had 40 and tower Santa Maria di Nazareth (Scalzi) had 1, but 10 towers did not have any. These bands are very crucial to "tying" the walls of the building together to prevent their separation if there was any movement, commonly earthquakes, in the tectonic plates below the surface. Tie bands could be placed in all towers as preventative maintenance where needed.

Vibrational data were considered an indicator of the stress felt by each tower. While a full structural analysis could not be completed by the project team, vibrational data seemed a reasonable indicator to hypothesize about the safety of each tower's structural integrity. Given two identical towers, one tower experiencing a lot of vibrations would be subjected to great stresses and thus, of the two, more likely to fail. Ultimately, vibrational data cannot show the chance of tower failure but rather comparatively indicates which towers are subjected to high forces when the bells are rung. It is the actual structural integrity of each tower that dictates its safety, not necessarily how hard the bells are rung since larger bells could be supported by a larger tower and sturdier materials.

The team was able to collect vibrational data for 5 bell towers, Appendix M. Of those tested, only SS Apostoli demonstrated significant shock and vibration in the belfry detectable by the smartphone IMU, Figure 25 and Appendix M. This is likely caused by the metal A frame holding the bells and that the bells in SS Apostoli were very large. Other towers did not show large vibrations when the bells were rung; the ringing vibrations were only marginally detectable above the noise threshold of the device.

The towers were rated based on a comparison between their vibration data. The two factors considered were the amplitude of the vibrations (how large the shocks were), and the period length of the vibrations (how quick the vibrations were). According to the Southern California Earthquake Center's website on earthquake shaking,

> The amount of damage to a building does not depend solely on how hard it is shaken. In general, smaller buildings such as houses are damaged more by higher frequencies... Larger structures such as high-rises and bridges are damaged more by lower frequencies...[81]

Thus, the higher the amplitude, the higher the force and shock on the tower, and the longer the period length (lower the frequency), the more damaging the vibration to the tower. The amplitudes and periods were rated separately. A rating of 1 was very poor for large amplitudes

[81] "Earthquake Shaking."

and long periods, and a 5 was excellent for small amplitudes and short periods, both undetectable in the case of a 5 rating. The towers were comparably rated as follows in Table 2:

Tower Name	Vibration Amplitude Rating	Vibration Period Rating
Santi Maria E Donato	5	5
San Geremia	4	3
San Sofia	3	4
SS Apostoli	1	3
San Angelo	4	1

Table 2: Vibration ratings for towers (1 is very poor, 5 is excellent).

Salvadore and other campanologists believe that the location of the supports for belfry frames impacts the building negatively. When the frame supports are started in the middle of the belfry shaft, it allows the vibrations to be dampened over the longer distance of the supports, and the belfry walls are stronger closer to the foundation of the tower.[82] In the study, all towers studied had belfry frame mounts located in the belfry. None had belfry frames that extended into the shaft of the tower. The rating system for this aspect of the tower could likely be a gradient based on the height that the frame supports were mounted relative to the tower heights, with a 1 being frame supports entirely within the belfry and 5 being low in the shaft. However, this study is limited to assigning a rating of one to each bell tower in the study.

The frame material was also used in determining safety, though it also impacts bell sound quality. According to campanologist Salvadore, the frame material of the belfry is very important. Wooden frames are much better at preserving the acoustics of the bell and the integrity of the tower. This organic material is not only traditional for frames, but also absorbs vibrations created when the bells are rung, preventing the structure from sustaining damage during bell ringing and enhancing the bells' sound.[83] As mentioned in the background, bells are

[82] Salvadore, Pietro.
[83] Salvadore, Pietro.

normally cast using metals since they continue to vibrate for a long period of time, thus producing a nice ring and lasting peel. However, metal's material properties would not benefit a belfry frame which is intended to isolate the bell vibrations from the tower. Frames constructed using metal, then, were considered to be detrimental to the tower's structural integrity since they transferred more energy from the bell's ringing to the structure. Similar to the impact large vibrations could have on the structure, this may increase the risk of cracking, holes forming, and bricks becoming loose. Thus, for the sake of this analysis, wooden frames were considered safe while metal frames were considered unsafe. The frame materials were collected as seen in Table 3 and Figure 41.1. Some towers were not accessible, so the belfry material could not be determined. The towers were then rated according to the material: metal frames received a one while wooden frames received a five. Frame type was also collected during the surveys, Table 3 and Figure 41.2, but the frame type has no known effect on the integrity of bell towers. More research would be necessary to determine which frame is better, so the frame type is not included in the safety rating systems.

Bell Tower Code	Frame Material	Material Rating	Frame Type
ALVI	Metal	1	A
ANGE	Wood	5	H
APOS	Metal	1	A
ASST	Wood	5	A
CANC	Wood	5	H
CATM	Metal	1	A
DONA	Wood	5	A
ERAS	Unknown		Unknown
EROS	Wood	5	H
FELI	Metal	1	H
FOSC	Unknown		Unknown
GERE	Metal	1	H
GIOB	Metal	1	H
GRIS	Metal	1	H
MARB	Metal	1	A
MIRA	Wood	5	H
ORTO	Wood	5	H
PIEM	Metal	1	A
SCAL	Metal	1	A
SOFI	Wood	5	H

Table 3: Belfry frame materials, types, and material ratings for bell towers

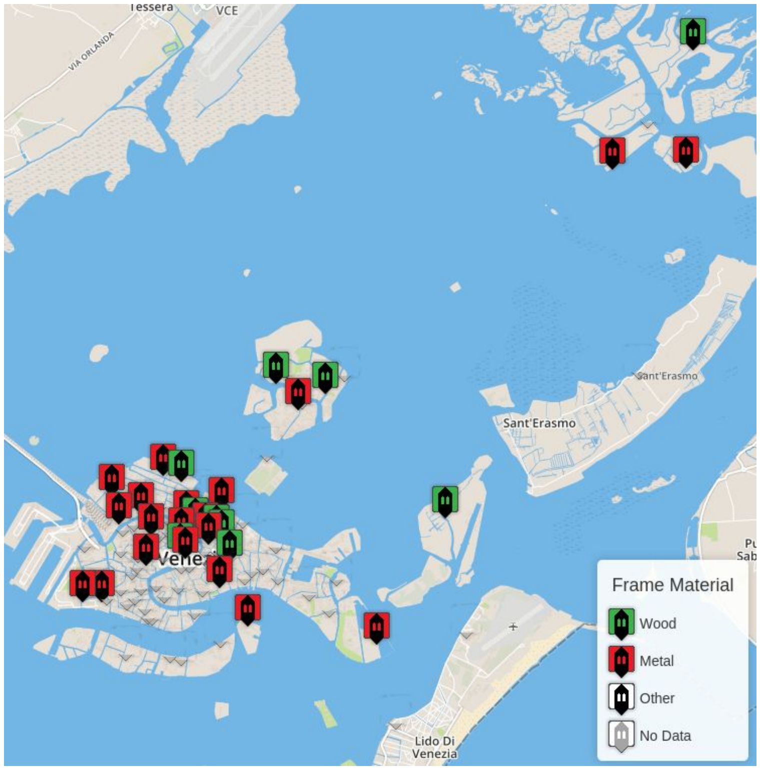

Figure 41.1: Belfry frame materials

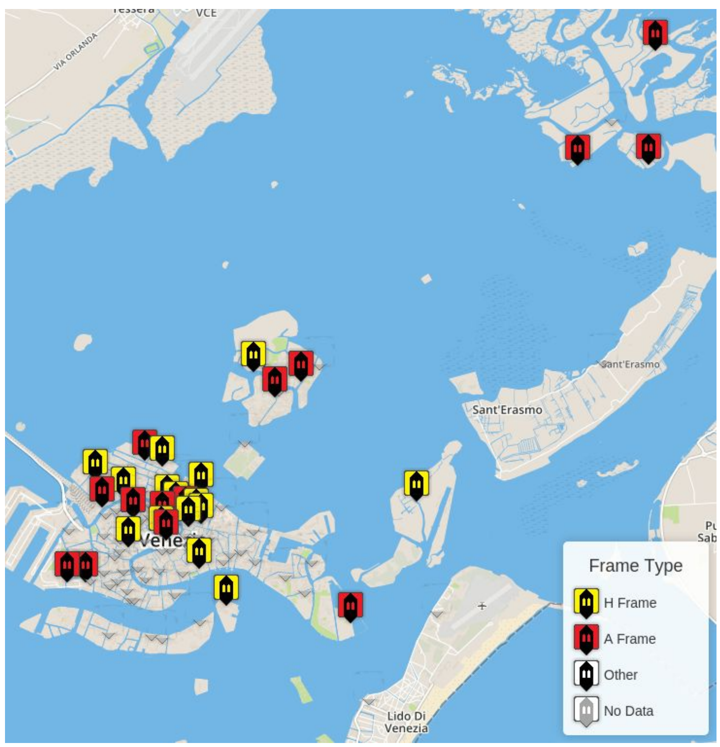

Figure 41.2: Belfry frame types

To separate the belfry from the whole tower, the safety ratings of the belfries were determined by comparing the same structural integrity factors described above as well as our experiences in each belfry. Additionally, analysis of the bells was important to bring into this rating. Twelve bells throughout the lagoon have been restricted from ringing due to safety concerns, so this became an important factor in the rating. This comparative average was then rounded to the nearest whole number to determine the belfry rating from very poor to excellent, Figure 42.

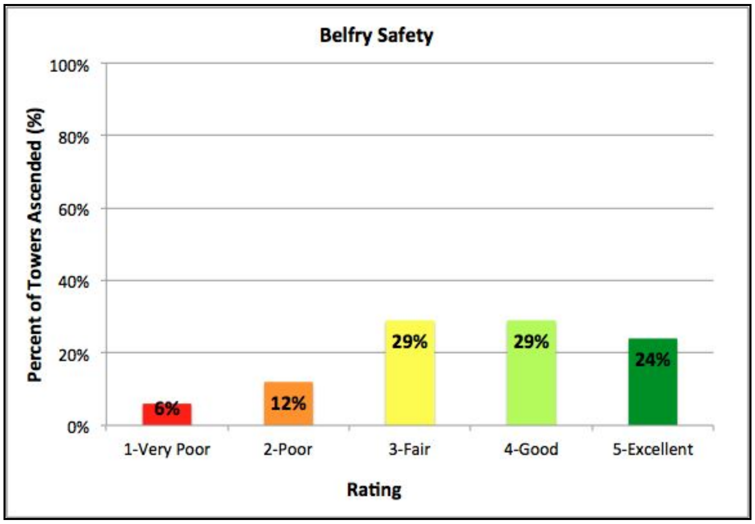

Figure 42: Belfry safety evaluations from 20 towers ranging from very poor (1) to excellent (5)

Each landing in the tower was evaluated for safety based on its observable structural integrity and our first-hand experiences in the towers, rated on a scale of 1 (poor) to 5 (excellent). From our experiences, the landings were usually used as storage space for miscellaneous items of the adjacent church. This made it difficult to maneuver around the landings and defined how safe a landing was. Once each individual landing was analyzed and given a rating, the average among the tower landings was taken to determine structural stability of the respective tower.

Now that the towers had safety ratings for all of their key features, weights were determined for each section based on our opinions, and percents were given to total 100%. In the future, once there is a deeper understanding of the towers, the weights may be adjusted as researchers see fit. We believed that the safety of the landings was worth 20%, the belfry 16%, the vibrational assessment and tilt were each 14%, frame type and quantity of cracks and holes were each 12%, and the damaged bricks and tie bands were each 6%. These percents were then multiplied by their respective ratings (1-5) and added together to be rounded to the nearest whole number to produce a safety rating that for that tower. Three bell towers, Santa Caterina e San Pietro, San Giobbe, and San Felice, were given a safety rating of one. A safety rating of two was given to San Geremia, Santa Maria dei Miracoli, Santa Sofia, and San Donato bell towers. Santa Maria degli Angeli, Santa Maria di Nazareth (Scalzi), and Sant'Alvise bell towers were rated at a safety rating of three. Santi Apostoli was the only tower to have a rating of four for safety. Thus, more than half of the towers, 65% of all towers ascended into, received a safety rating lower than a five. The remaining towers, San Pietro Martire, San Canciano, San Martino, San Giovanni Grisostomo, Santa Maria Assunta, and La Madonna dell'Orto were each given a safety rating of 5. Although San Martino was drastically leaning towards one side, restoration and safety precautions have been implemented into the tower to preserve and monitor its structural integrity. This tower can be used as an example when planning similar construction on other towers. Results are comparatively shown in Figure 43.1 and shown for each bell tower in Figure 43.2. Ratings excluded the public towers of San Marco and San Giorgio and also excluded the Sant'Erasmo, Sant'Eurosia, and Santa Fosca bell towers because we were not able to enter them.

Figure 43.1: Tower safety evaluations from 20 towers ranging from very poor (1) to excellent (5)

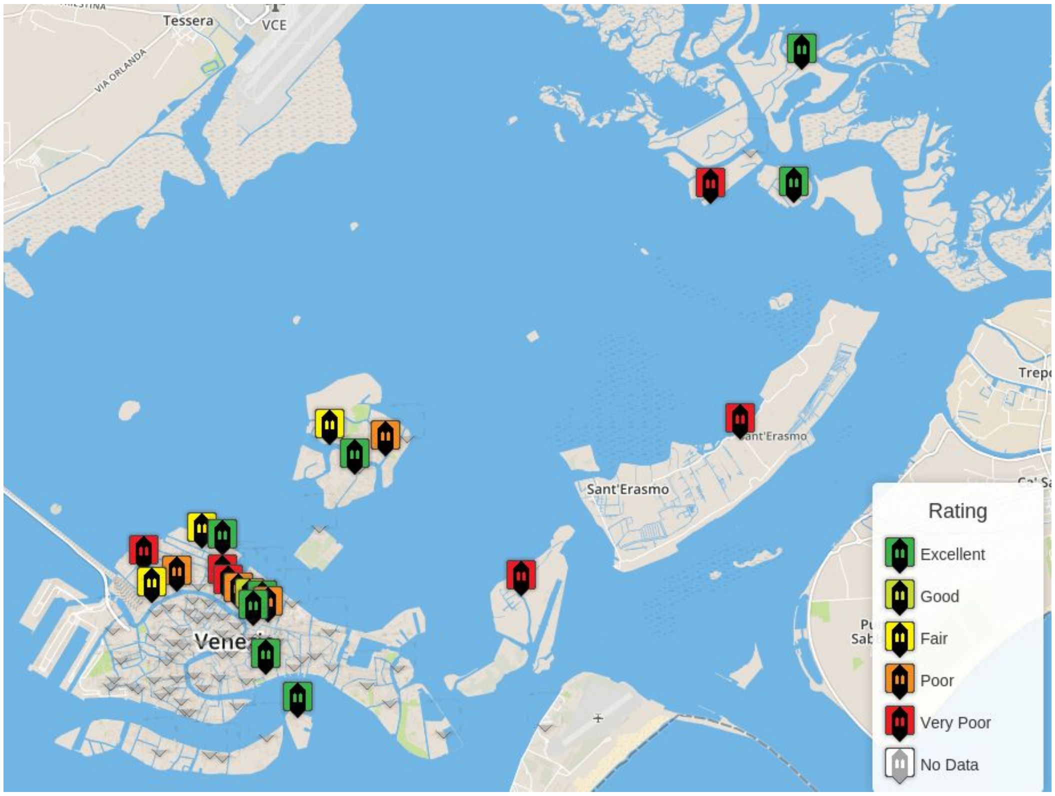

Figure 43.2: Safety ratings of towers

4.1.4 Accessibility of the Bell Towers

We defined accessibility as having adequate lighting throughout the tower, stable railings for each level within the shaft, sturdy stairways or ramps from the bottom of the tower to the belfry, and having little to no obstructions in the entrances and stairways of the tower. We also took into consideration if there was adequate room in the belfry for people by analyzing the area of the belfry, the distance the clapper was from the floor, the the area of the door leading into the belfry. Other characteristics of the tower that were important to note in terms of accessibility were if the bell tower had a public entryway into the tower or if a visitor had to go through the church in order to ascend up the tower.

Lighting of the shaft was one of the main accessibility concerns. As a team we broke our lighting data collection into two specific fields, artificial lighting which came from lighting fixtures and natural lighting which came from windows. It was important to note that 10 of the 20 towers visited had a form of artificial lighting within them. This means that there was at least one lighting fixture that worked within the entire tower. Out of these 10 bell towers with some form of artificial lighting, only two had working fixtures on each landing within the structure. These two bell towers with the best artificial lighting were Santa Maria Assunta in Torcello and Santa Sofia in Cannaregio. In terms of natural lighting, 16 out of the 20 towers had at least one window within the shaft of the structure. Out of these 16 bell towers, only seven had windows present on each landing within the shaft. With all the data that was collected on lighting, both artificial and natural, we noted that five bell towers only had one form of lighting, natural lighting, throughout the entire building. Each one of these towers only had windows on half of their landings and made it difficult to navigate through each landing without a flashlight. Two bell towers, San Giovanni Grisostomo and Gli Scalzi, both in Cannaregio, did not have any form of natural or artificial light, therefore making it difficult for more than one person to ascend the tower at a time.

Another concern for the accessibility of the towers was if the staircases have railings and if present, would these railings be stable enough for public use. 14 of the 20 towers surveyed had at least one railing within the shaft of the bell tower. This means in these 14 towers, there was a minimum of one stable railing within the entirety of the structure. Of these 14 bell towers, nine had railings on every single staircase within the shaft. Though this seems impressive in terms of accessibility, only three of these nine towers had railings that we deemed stable. These three bell towers with the most stable railings are Santa Maria Assunta, La Madonna dell'Orto, and San Giovanni Grisostomo. Four of these 20 bell towers that were visited had no railings anywhere within the structure, making the climb up to the belfry very dangerous and difficult since there is nothing for the climber to hold onto to maintain their balance. The four bell towers with no railings included San Donato, San Giorgio, I Miracoli, and Gli Scalzi. The remaining two bell towers that were surveyed are Sant'Erasmo and Sant'Eurosia. Sant'Erasmo did not have an accessible shaft and we ascended into the belfry by leaning a ladder against the exterior side and climb into the belfry through a window. Sant'Eurosia was not deemed safe for us to survey from the interior so no railings could be documented.

Other characteristics for documenting bell tower accessibility was if the internal shaft was made up of ramps or staircases within its landings. This was an important quality to analyze as it helped determine whether the structure was safe for the public to visit. Out of the surveyed 20 bell towers, only three had ramps while 17 contained staircases with landings. The three bell towers with ramps included Santa Maria Assunta, Santi Apostoli, and La Madonna dell'Orto. These ramps were all made out of concrete and all had sturdy railings to help the climber keep their balance.

Therefore these three bell towers were deemed to have the most accessible climbing experience from our personal observations within the tower. The remaining 17 bell towers with staircases and landings were further analyzed to determine whether they could be considered accessible. We also had to determine if the stairs within each landing's staircase were in overall good condition. Many bell towers had rotting wood, cracks, and unstable steps for each set of stairs. Across the 17 bell towers with staircases, eight percent of all the stairs in total were considered to be bad. Specifically, out of these 17 towers, we encountered 1,472 stairs and of these, 118 steps were what we deemed to be in bad condition, thus affecting the tower's overall accessibility. In addition to looking at specific steps, we also noted the number of landings that we visited throughout the entire fieldwork period to be 84 landings. Out of these landings we noted that 43 had at least one bad step within its respective staircase. This translates to 51% of all landings had at least one bad step.

The amount of obstructions present on each landing within the shaft of the bell tower was also important to document. Out of the twenty towers that were visited, we documented our findings on whether or not there was a clear path for us to walk through on each landing or if there were obstructions that made walking difficult. We defined any obstruction or clutter to be anything placed in the way of the entrances and stairways of the structure. This could include stored artifacts, chairs, cleaning supplies, large paintings, heavy boxes, or anything else that took up space within the staircase landing. From the 20 towers visited, only seven bell towers were considered to have little to no obstructions when walking through each landing. 13 towers were then deemed to be difficult to maneuver around due to their cluttered landings.

An overall structural rating of each staircase was then determined based on how supportive it was and its ease of use, based on personal experience. These data points were used to average the staircase rating per tower as well as the obstructions rating of each staircase. These values were then combined to assess the towers' staircases as a whole, and then that rating was compared with the percentage of bad steps per tower to generate a final rating. The final rating was then rounded to the nearest whole number to express a value from very poor to excellent, Figure 44.

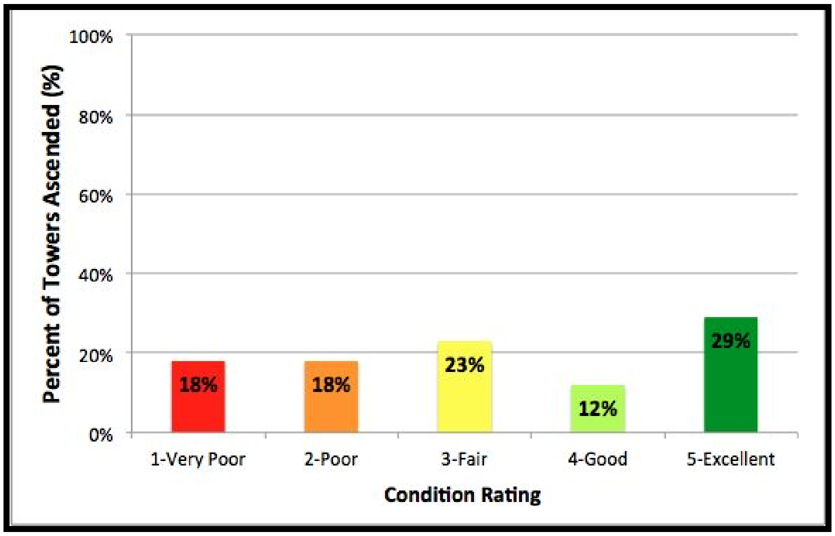

Figure 44: Tower accessibility from 20 towers ranging from very poor (1) to excellent (5)

Three bell towers had an overall rating of poor (which was ranked as 1) were Santa Caterina e San Pietro, San Giobbe, and San Felice. Six bell towers had an overall rating of excellent (which was ranked as 5) and they were San Canciano, San Pietro Martire, San Martino, San Giovanni Grisostomo, Santa Maria Assunta, and La Madonna dell'Orto.

Once we reached the landing before the belfry, we paid special attention to the difficulty of entering the belfry. We took dimensions of the door leading to the belfry and determined that the most important dimension in terms of accessibility was the width. According to the International Building Code, a proper door should have the width of 81 centimeters.[84] We determined that 14 out of the 20 bell towers visited had a belfry door width below this code specification and therefore cannot be deemed properly accessible.

Additionally, we documented the height from the floor of the belfry to the bottom of the clapper on the bell in centimeters to help determine if a person could safely walk under the bells. We organized our data based on if our measured distances were above or below the average height of a person, which according to WebMD, is 170 centimeters.[85] We determined that out of the 46 bells that we had this measurement for, only 17 were far enough off the ground for the average person to walk under. 29 bells were hung below the average 170 centimeters, making the

[84] International Building Code 2009
[85] "Average Human Height"

ability to walk under these bells impossible, therefore, impinging the overall accessibility of the tower.

When assessing the belfry, the area of the belfry door, area of the belfry, and the shortest clapper to floor distance was compiled. We chose these values because if we were to open a bell tower to the public, it would be important to make sure the bells are not an accessibility hazard and that the average person could comfortably move within the belfry. This rating of accessibility was also based on our personal experience in the tower, and the results of these ratings can be seen in Figure 45.1 and Figure 45.2.

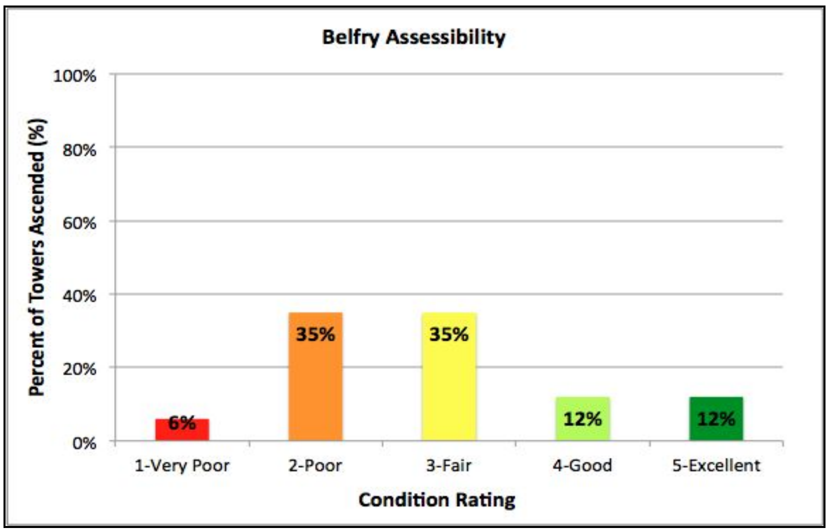

Figure 45.1: Belfry accessibility from 20 towers ranging from very poor (1) to excellent (5)

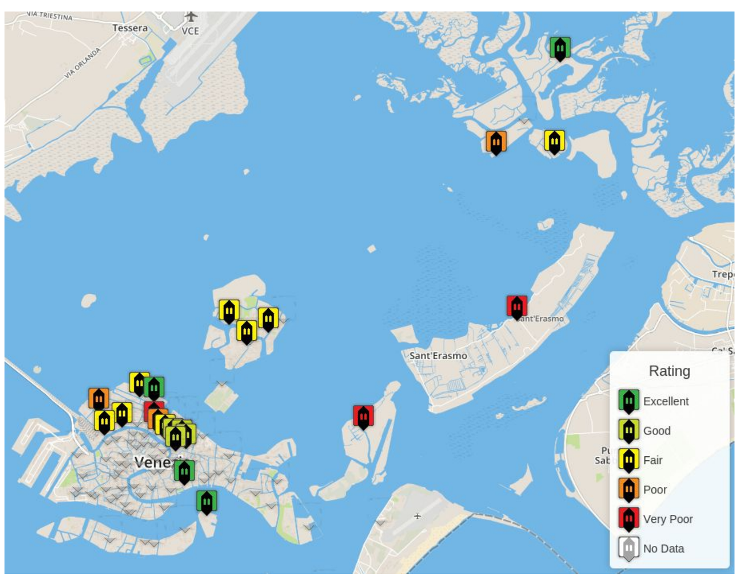

Figure 45.2: Tower accessibility ratings

Only one bell tower had an overall rating of poor (which was ranked as 1) and it was San Martino. Though it is impressive that only one out of 20 bell towers we ranked to have a poor belfry accessibility, only two bell towers had an overall rating of excellent (which was ranked as 5). These two bell towers were Santa Maria Assunta, and La Madonna dell'Orto.

Another feature of each bell tower that was documented was whether the bell tower had to be accessed through the church or if it was a freestanding structure. We documented that 16 of the 20 bell towers were only accessible through the church. The remaining four bell towers have varying reasons for why they have entrances that are separate from the church. These four towers included Santi Apostoli, Santa Maria Assunta, San Donato, and Sant'Eurosia. The entrance to Santi Apostoli was actually located in a clothing store that took up the entire foundation layer of the bell tower. Santa Maria Assunta and San Donato are two bell towers that are both freestanding from their respective churches. Sant'Eurosia's bell tower is considered to be inaccessible unless the climber was willing to lean a ladder against the exterior of the tower and climb into the belfry through the belfry windows.

Figure 46 displays which towers would be the easiest in which to hold public tours by combining ratings from four categories. From this graph, it is easy to determine which towers need more assistance in maintenance and/or minor improvements. The first three towers (Sant'Erasmo, Sant'Eurosia, and Santa Fosca) were considered off limits to the public due to their current state or since they were completely inaccessible. For instance, the bell tower of Sant'Eurosia was only accessible by scaling the outside of the tower with a ladder and removing a window to climb into the belfry.

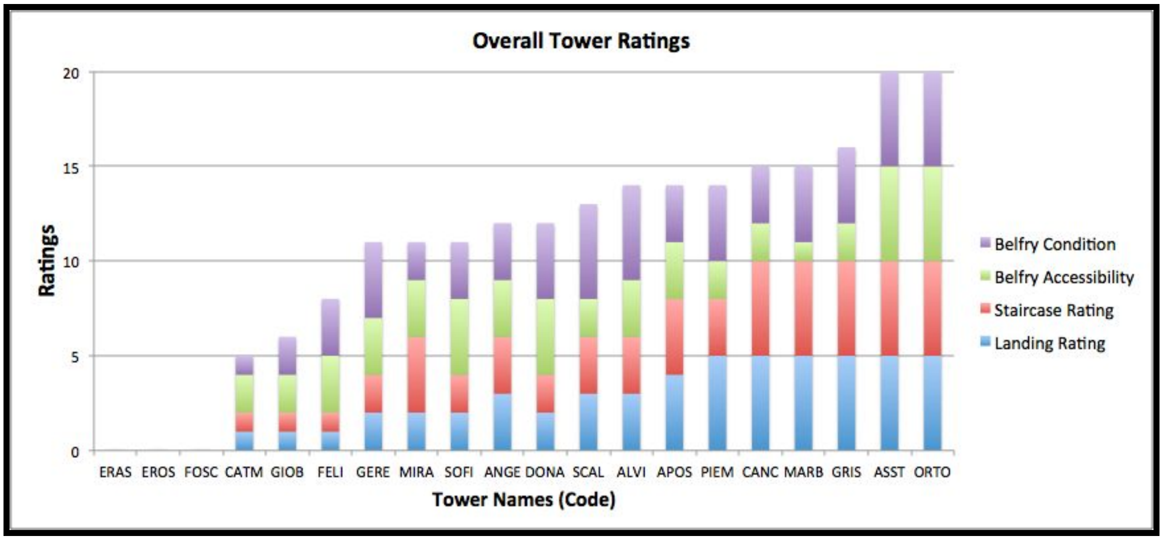

Figure 46: 20 towers surveyed based on conditions and accessibility

4.1.5 Overall Impressions in Relation to Opening Towers to the Public

Based on the team's experience surveying and ascending the towers, a ranking system was devised to generally assess the overall quality (in terms of condition, accessibility, and safety) of each of the 20 bell towers. This system was composed by sorting through our data fields and general tower observations to produce a rating of 1 through 5 in addition to including our opinions from a first-hand experience. A bell tower rated one had serious safety concerns, little to no accessibility, and our overall impression of the condition is very poor. These bell towers would need a significant amount of restoration before they could be deemed safe, sturdy, and secure. A rated number two bell tower is better than a rated number one tower, but it still has significant safety concerns, requires a lot of cleaning, in terms of removing guano from birds and any other particulate that could be hazardous to health or obstructions that make traversing the tower dangerous, and the overall condition demands a large number of improvements. A rated number three bell tower has few significant safety concerns. Some restoration would be necessary to improve accessibility and overall condition. A rated number four bell tower had little to no safety concerns, is easily accessible and conditions are good overall. A rated number five bell tower was ideal. All restoration efforts have already been made and because of this the safety, accessibility, and general condition is superb. Specific characteristics of each tower rating are further explained below in Table 4.

Criteria	#1 Rating	#2 Rating	#3 Rating	#4 Rating	#5 Rating
Space available on landing	Cluttered landings, no path for walking from level to level	Cluttered landings for storage, somewhat of a path for walking around	Landings are still used for storage, but there is a clear path for walking	clear landings, stairs, and/or ramps	Open and spacious with clear landings and stairs
Wall cleanliness	Graffiti on walls everywhere, both on interior and exterior walls	Interior and exterior walls of shaft and belfry are very dirty	Interior and exterior walls have some dirt and markings on them	Clean walls on interior and exterior	Regularly cleaned internal and external walls
Wall integrity	Cracking all throughout the shaft and the belfry	Few cracks within the walls of the shaft and belfry	Some interior bricks are crumbling	Bricks everywhere are in decent condition	Bricks everywhere are in great condition
Window netting	No netting anywhere within belfry windows	Some windows within belfry have nettings	Majority of windows in belfry have netting	All windows have nettings as a screen	All windows have nettings as a screen
Bell structural conditions	Heavily chipped bells, chunks missing	Most bells have chipping	Some of the bells have chipping	Little to no chipping for each bell	Bells are in perfect condition
Bird droppings on bells	Thickly covers all the bells	Covers all of the bells	Covers some of the bells	Covers little to none of the bells	Not present in the tower
Bird droppings in tower	Inches of bird poop	Bird poop everywhere	Bird poop in some parts of the tower	Little to no bird poop within the tower	No bird poop anywhere in tower
Bird infestation	Belfry is covered with bird feathers, bird nests all throughout attic	Belfry has bird feathers everywhere, constantly has birds flying in and out	Belfry has a lot of bird feathers, occasionally has bird flying in	Belfry has little to no bird feathers, no presence of birds	Belfry has no bird feathers or any birds present

Lighting in shaft	No lighting, very dark, flashlight needed	There is lighting on each level, except it no longer works	Lights work on a majority of the landings	Lighting works on each level	Lighting is everywhere, always works
Landing railings	No railings in any levels	No railings for each landing within the shaft	All levels within the shaft have railings, some are cracking and are not sturdy	All levels within the shaft have railings, all are in good condition and are fairly sturdy	All levels within the shaft have railings, all are in great condition and are sturdy
Landing conditions	Holes everywhere on the floors of each landing, very difficult to walk around	Many holes in the wooden stairs and landings	A few holes within the wooden landings, does not obstruct accessibility	Little to no holes within the wooden landings, barely any obstructions for accessibility	No holes within landings, no obstructions
Animal remains	Significant amount of carcasses of birds within belfry	Many carcasses of birds within belfry	Few carcasses of birds within belfry	Little to no carcasses of birds within belfry	No carcasses of birds within belfry
Wood conditions	rotting	Wooden stairs are in-tact, but not sturdy	Wooden stairs are in decent condition, mostly sturdy	Wooden stairs are in good condition, very sturdy	No rotting wood anywhere, no holes anywhere
Stairway or ramp sturdiness	crumble when walked upon	Many holes in the wooden stairs and landings	Few holes in the wooden stairs and landings	Ramps are sturdy and secure for each landing Stairs or ramps are very sturdy and very secure	Stairs are very sturdy and very secure
Plant presence	growing everywhere	Growing in many places of the belfry	Growing in small sections of belfry	Little to no plant growth	No plant growth

	within the belfry				
Bell heights from belfry floor	Very low hanging bells, serious safety issue	Bells are very low and difficult to stand in belfry with others	Maneuvering around bells is manageable but difficult	Ducking under bells is slightly needed	The bells are not hanging too low to the ground
Occupancy in belfry	Only one person can fit in the belfry at a time	Not very spacious, a few people can fit in the belfry at a time	Somewhat spacious, can have a very small group of people	Spacious, people can walk around comfortably	Belfry is very spacious, can easily walk around
Belfry cleanliness	Weeds growing, very dirty, bird carcasses and guano	Weeds growing, bird guano	One or two weeds growing	Dirty, but only a simple cleaning needed	Extremely clean
Entering Belfry	Belfry entrance is very small and assistance is needed	Getting into belfry is difficult, but manageable	Getting into belfry is manageable	Getting into belfry is easy and can be done safely	Entering the belfry requires no extra effort

Table 4: Rubric for scoring bell towers on condition

Table 5 shows each bell tower in which we conducted ascended surveys, and an overall ranking based on the criteria above. These ratings (numbered 1-5) were also based on the data presented in Figures 42-46. Further, Figure 47.1 displays these ratings in a bar graph to show the percent of towers falling within each overall rating, while Figure 47.2 displays the individual towers in the Venice Lagoon.

Bell Tower	Ranking
Santa Caterina e San Pietro	1
Santa Fosca in Cannaregio	1
I Miracoli	2
Gli Scalzi	2
San Felice	2

Sant Eurosia	2
San Donato	3
San Geremia	3
I Santi Apostoli	3
San Canciano	3
San Giobbe	3
San Giovanni Grisostomo	3
Sant'Alvise	3
Santa Sofia	3
Sant'Erasmo	3
Santa Maria degli Angeli	3
La Madonna dell'Orto	4
San Pietro Martire	4
San Martino	4
San Giorgio	5
Santa Maria Assunta	5
San Marco	5

Table 5: Bell tower overall rankings

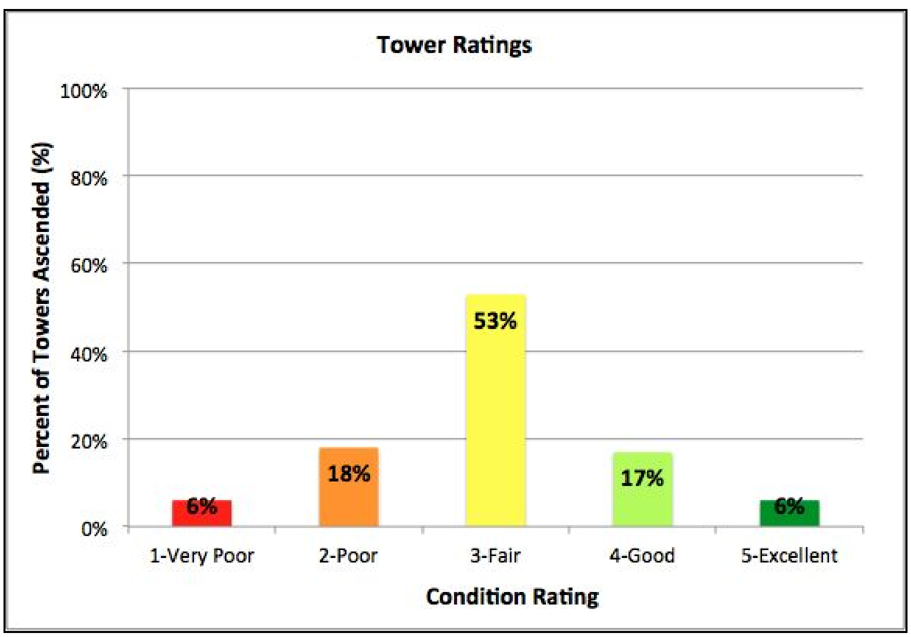

Figure 47.1: Overall bell tower ratings

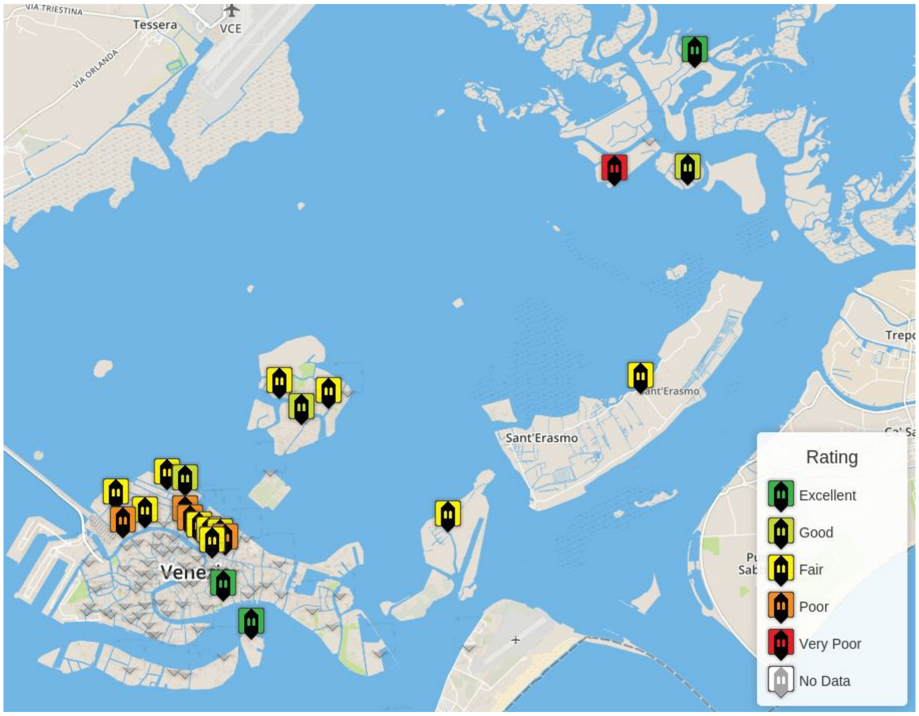

Figure 47.2: Map of overall impressions for towers

4.1.6 Analysis of Methods

To obtain necessary information about the foundation and exterior of the bell tower, we had to observe it visually from the outside. However, we encountered many circumstances where only the upper shaft and belfry were visible. These gaps were noted in the spreadsheet under the columns “Connected to” and “Visibility” which distinguished the visible parts of the bell tower.

In order to document each landing properly, it was important to focus on them individually rather than document by category, steps, windows, or cracks. This proved to be helpful because the data was recorded by landing and entered into the master spreadsheet in that order. The tools used during this data collection proved to be extremely beneficial in data collection.

Within the belfry we experienced a few issues with each method of data collection attempted. With regards to dimensional data collection, there were issues ascertaining the height of many belfrys due to extremely high ceilings or obstructions from crossbeams and other structural or frame supports.

The exterior landscape was also attempted to be captured from the belfry through the use of cell phone cameras and compiled into a panorama using free software called Hugin. There was mild success in this aspect of the endeavor. The main hindrance was the wire mesh present in many of the windows of the belfry. In addition, some of the belfrys were arranged in such a way that it was not possible to capture some angles of the landscape necessary to construct a 360 degree panorama.

There were also attempts to use photogrammetric software to create 3D models of the interior of the belfry. The software excelled at creating models when a series of photos were able to encompass an object in its entirety. However, the belfries contained a plethora of objects and thousands of faces to capture. Many models were simply too fragmented to ascertain any useful information that would not otherwise be available from a simple video. Of the half dozen belfry models attempted, only 3 or 4 resolved to a distinguishable form, and of those three, none were complete. At best, 65 percent of the interior was captured. To adequately capture all of the data to create a 3D model, many hundreds or thousands of photographs would have to be taken in order to render a model with acceptable detail.

Photogrammetric reconstruction was also attempted on the bells in each of the belfrys. This had a much greater rate of success as compared to the belfry models. In a majority of the trials, a clear 3D model of the bell was generated that accurately captured the bells' artwork and engravings, general condition, shape, and size. In cases where the software failed, the problem was typically the inability to capture clear photos of the bell. The frame of the belfry sometimes obscured the bell, or the surrounding structure made it physically impossible to capture an image of some sides of the bell. On occasion, as was the case with La Madonna dell'Orto, the bells were so high they could not be photographed even with cameras on selfie-sticks. The failed trial produced no 3D models, but all of the raw photographs remained stored in the Google Drive and could be reused in the future and combined with new photographs.

4.2 Advancement of Online Applications

The three applications used to publicize the information collected about bell towers and bells were Venipedia, the Bells Application, and the Cartography Application. Before changes were made to the applications, a user could navigate between the applications in the manner displayed in Figure 48:

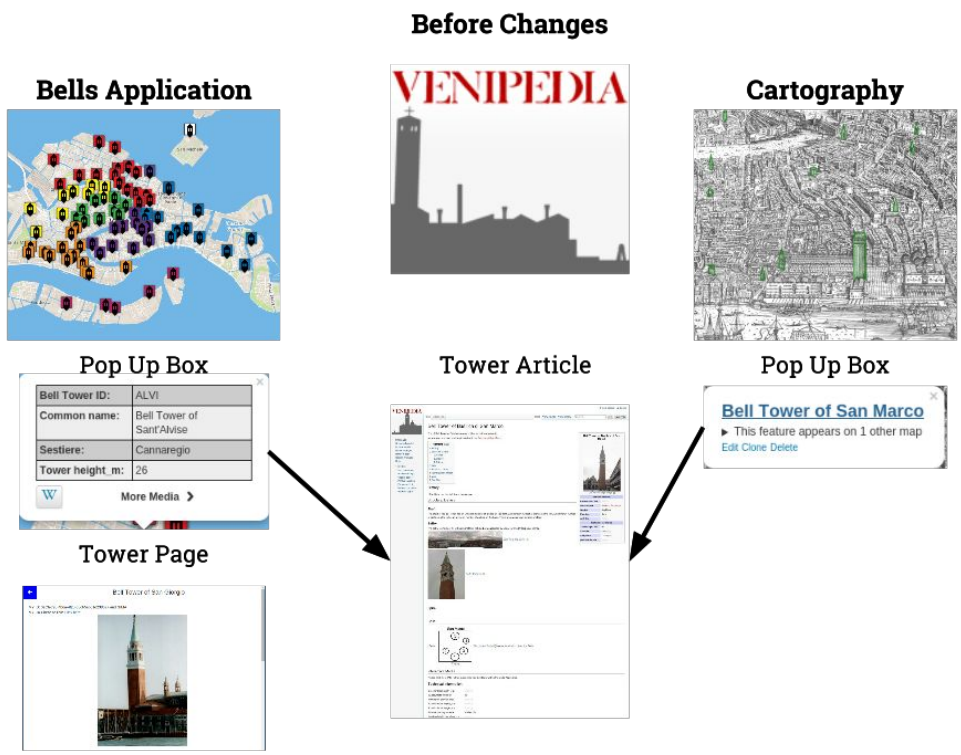

Figure 48: User navigation before application changes were made. Black arrow represents user access flow.

In the past, a user could reach the Venipedia page from both the cartography and bells application pop up boxes. However, there was no way to navigate from Venipedia to the Bells Application to see the unique information about the bell towers stored there. This was modified during this project as seen by the red arrow in Figure 49:

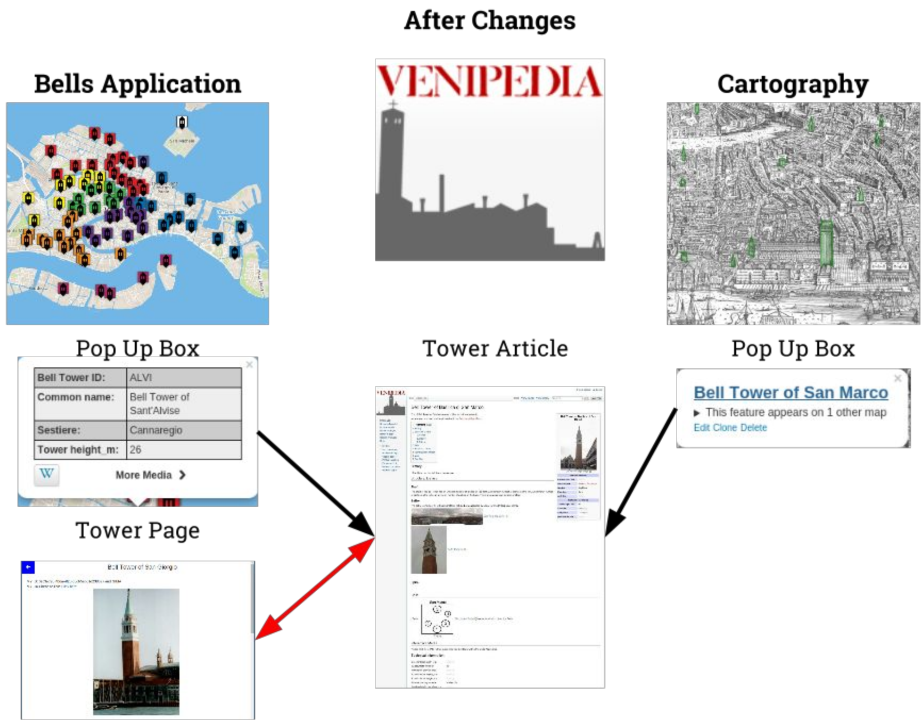

Figure 49: User access between applications with changes from this project shown in red.

Venipedia users can now reach the tower page of the bells application, allowing them to view the panoramas and audio for that bell tower. Also from a tower page in the bells application, the user can access Venipedia. The applications themselves were also modified and improved as shown in the following three sections.

4.2.1 Improved Venipedia Pages

Singular and plural Venipedia pages (Bell, Bells, Bell Tower, and Bell Towers) were updated with our new data and edited. These can be seen in Appendix J. All of the towers visited had their own Venipedia page before the project started, so the team simply updated the displayed information for each page and modified the template.

The team focused on modifying the Venipedia page template for bell towers and did not make significant changes to the Bells pages as the Venipedia tower pages were seen as the connecting elements of the three applications. The team desired to add interactive content for the bell tower Venipedia pages, but this was not possible since Venipedia did not support the iframe

HTML tag. Thus, a link was added to each bell tower article that allowed a user to visit the Bell Application page for that tower, which would store the models instead, as seen in Figure 50:

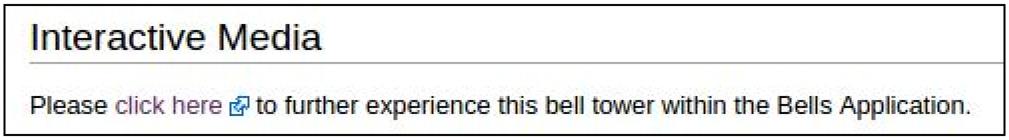

Figure 50: Link from Venipedia to Bells Application More Info page.

Images in Venipedia were only thumbnails, so a link was added on all photograph captions that, when clicked, allowed a user to view the original photograph at full resolution, as seen in Figure 51.

Figure 51: Link below image allowing full resolution picture to be seen.

Perhaps the link could have been applied directly to the photograph, but such a way was not immediately obvious due to the way the templates were made with the database files. Another link was added to bring a user to the detailed report on the tower that was generated by

Alberto Lionello in his book, *Tecniche Costruttive, Dissesti E Consolodamenti Dei Campanili Di Venezia*. This addition can be seen in Figure 52:

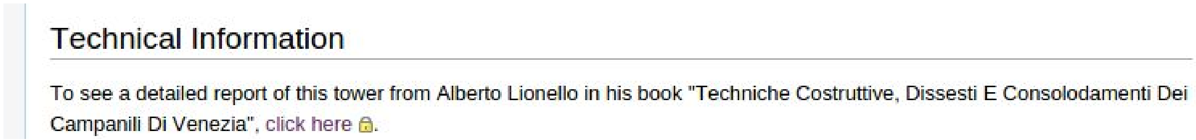

Figure 52: Link navigating user to tower data collected by Lionello.

The template was finally modified to reduce the number of unknown or undefined objects displayed in the page. This involved properly checking for null and missing data and resulted in eliminating odd text output seen in Figure 53. Examples of a bell tower and bell Venipedia page can be seen in Appendices K and L.

Figure 53: An undefined object (shown by red box) displayed on the San Giorgio page.

4.2.2 Updates for Online Bells Application

Since this was the dedicated application for viewing collected data, most time was invested in its development specifically. The main map interface was updated with the following enhancements seen in Figure 54:

1. The map zooming was increased to allow all of the bell towers to be seen at once
2. Documentation was updated
3. Bell Tower markers changed to look more like a bell tower
4. Layers were expanded by default so a user knew multiple layers were present
5. Outdated 25th VPC anniversary information was removed

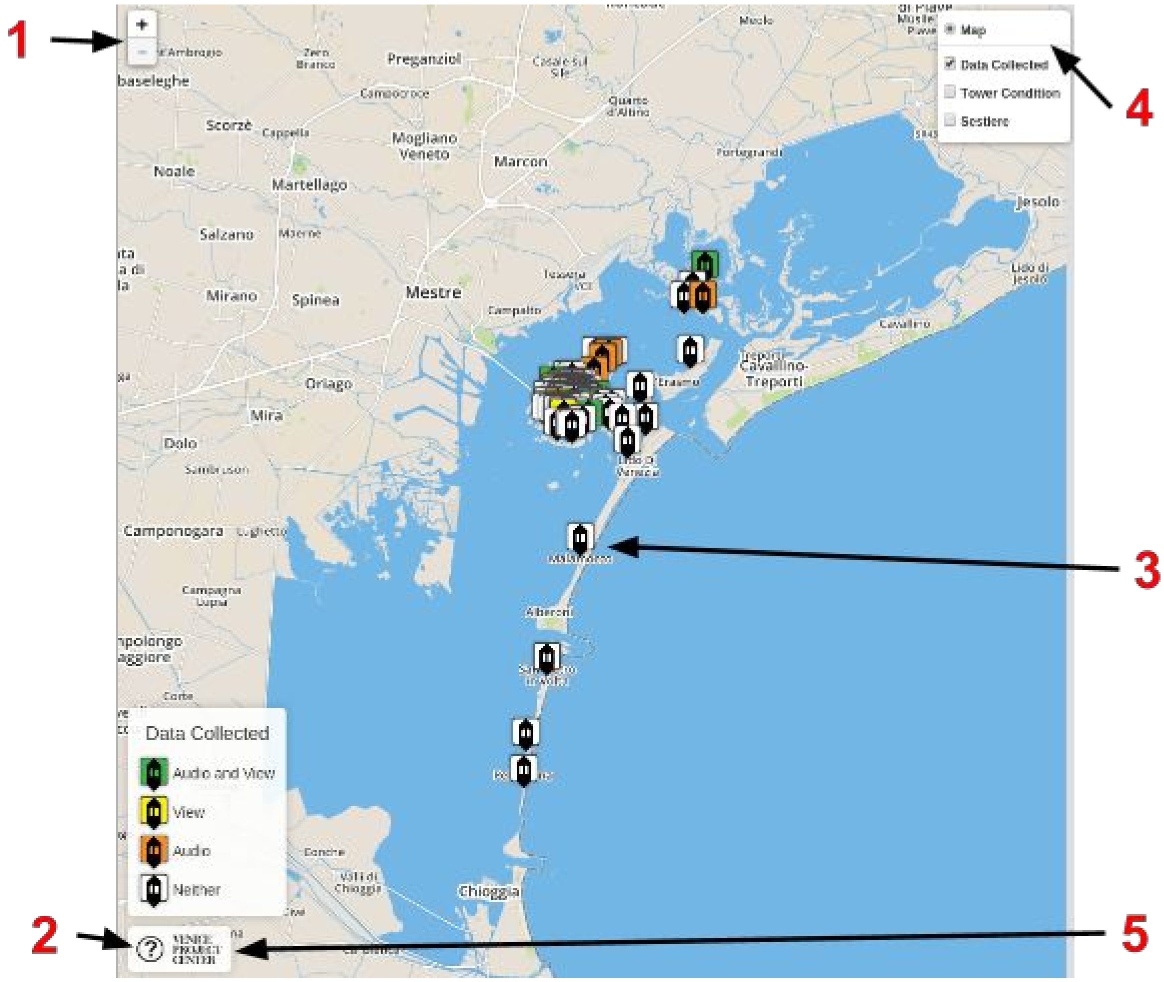

Figure 54: Changes to main map interface

The existing layer for tower data was modified as shown Figure 55:

1. Colors based on information stored in the database as opposed to hardcoded values in app
2. New color code to associate green with “good”, in this case, completed data
3. Legend Changes:
    - Legend updated to close when layer was deselected
    - Legend size reduced to allow more of map to be seen
    - Legend title changed
4. Layer title changed from “Bell Towers” to “Data Collected”

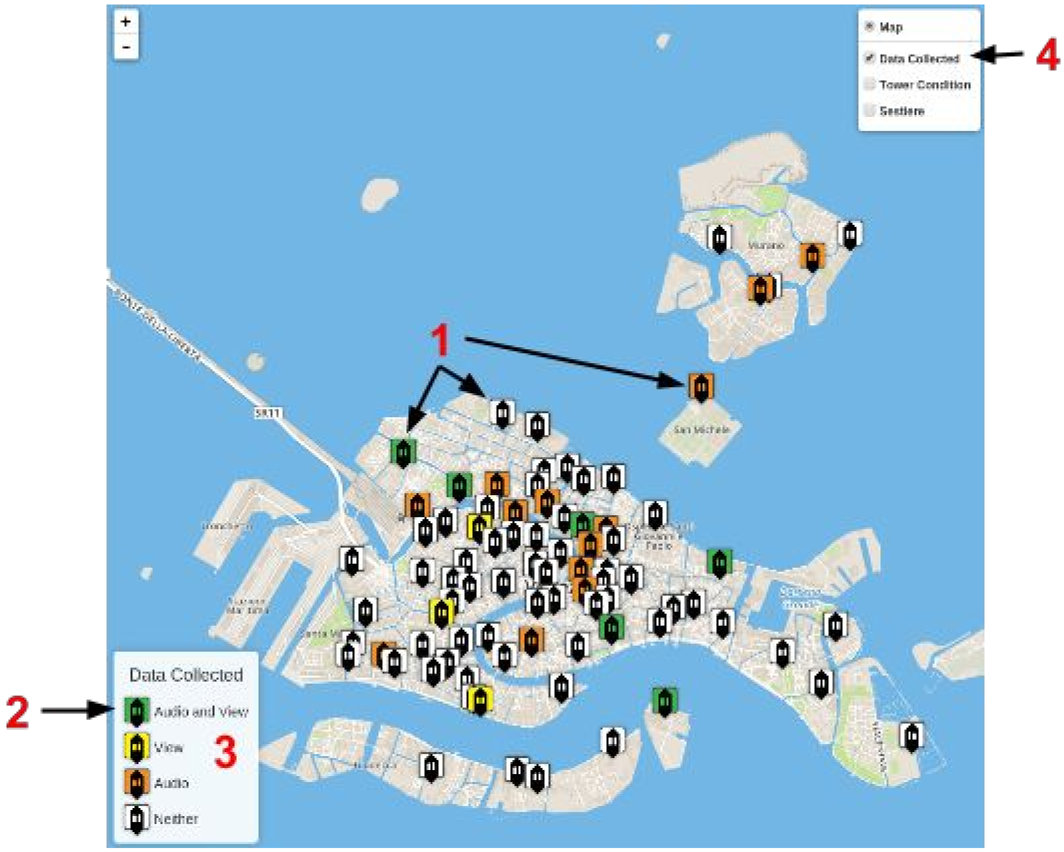

Figure 55: Changes to Data Collected Layer

Three more layers were created to illustrate the new rating system of the project: Tower Safety, Accessibility, and Overall Rating. When the layer was loaded, the towers were color coded according to the rating value stored in the database. An example of the Tower Condition layer is seen in Figure 56:

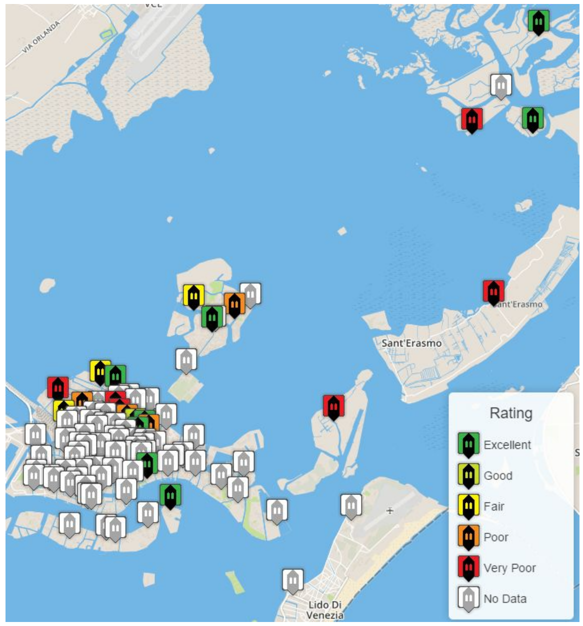

Figure 56: Tower Safety layer

Two additional layers provided a way to visualize the types and materials of belfry frames. Belfry frame types were classified as A or H frames, Figure 57.1, and the materials were either wood or metal, Figure 57.2.

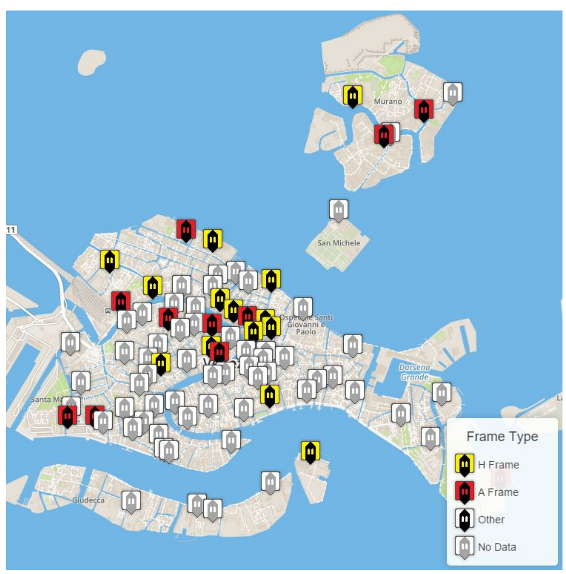

Figure 57.1: Belfry frame type. Red is A frame and Yellow is H frame

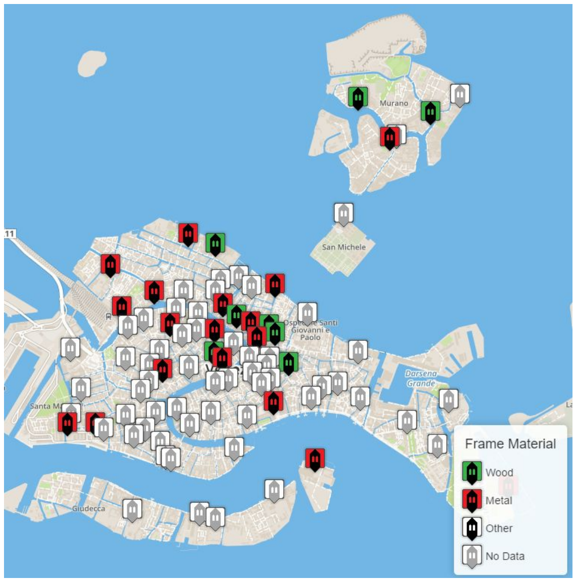

Figure 57.2: Belfry material type. Red is metal and Green is wooden

Another new layer colored the bell towers by Sestiere, allowing them to be more quickly identified if someone was trying to find bell towers by sestiere, Figure 58, since most tourists are unfamiliar with the Vicariate. All of the new colors in the map and associated legend were created during this project.

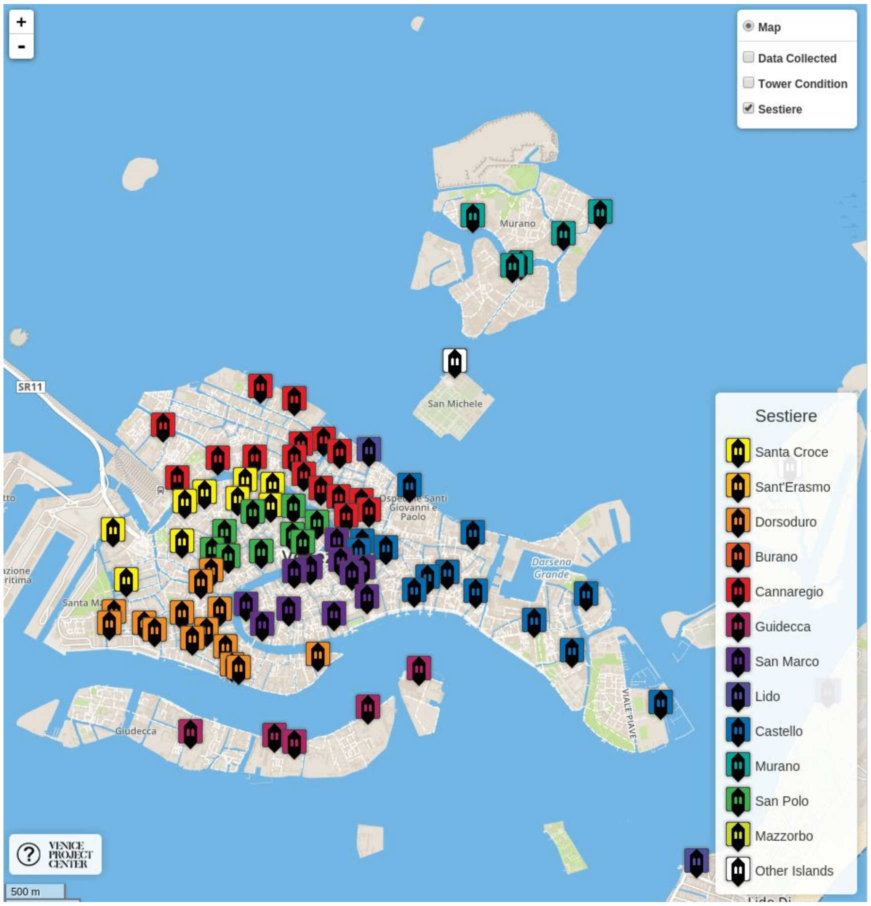

Figure 58: Tower sestiere layer

The pop-up page displayed when a tower was clicked, and it was modified as seen in Figure 59:

1. Play button for local storage audio removed
2. Label changed from "more-info" to "More Media"

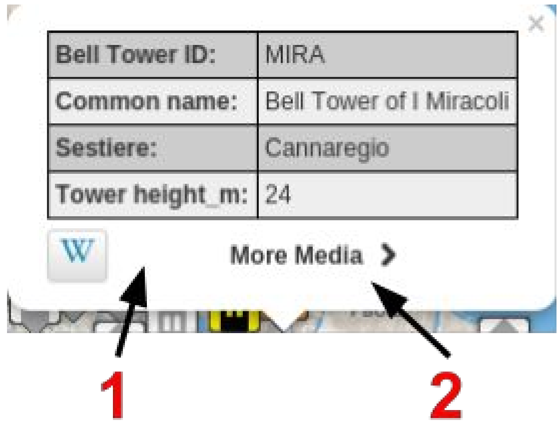

Figure 59: Changes to pop-up interface

The reason the play button was removed was because it relied on audio stored locally on the web host instead of on information links contained in the database. Since new audio was collected and displayed on the More Media page, it was redundant. Additionally, removing this play button allowed longer audio clips to be saved for the bell chorus audio since the implementation of the play button disallowed stopping the audio once it began to play on the popup.

Finally, the More Media page for the tower was modified in several ways, Figures 57 - 61:

1. Title displayed for bell tower and also added for tab/window title (used to be undefined)
2. Picture of tower displayed. Clicking image opens full resolution. Allows quick identification of tower from the ground.
3. Proper headings throughout media content
4. Panorama for tower linked to full resolution version by clicking.
5. Panorama explorable by scrolling image, similar to Wikipedia formatting.

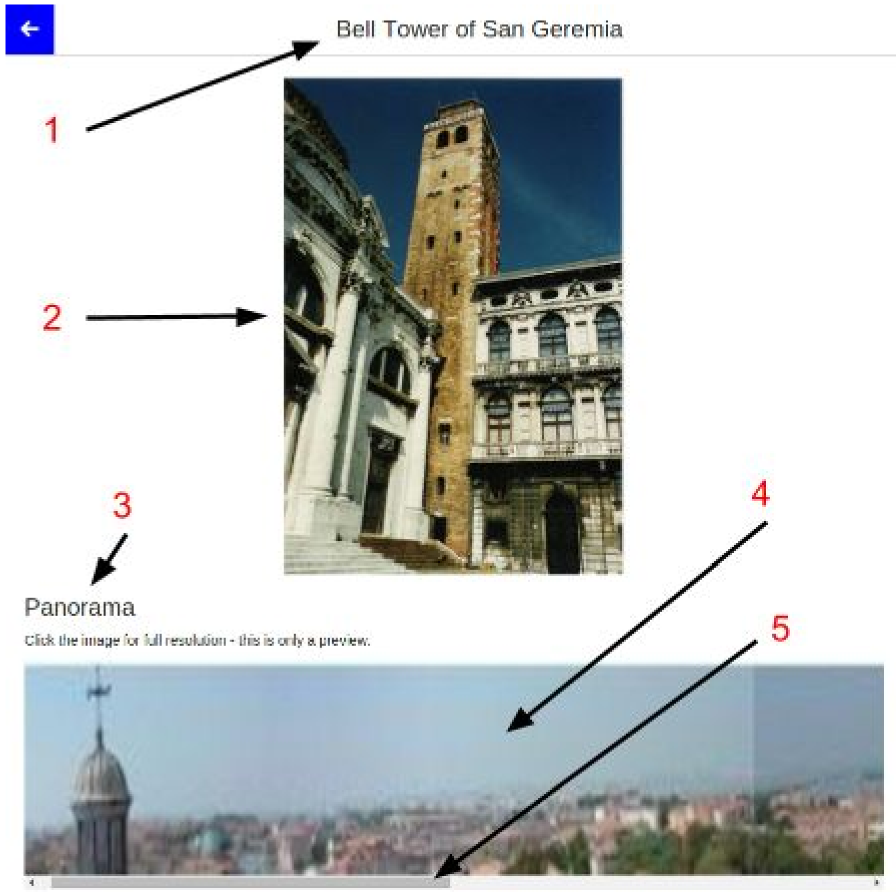

Figure 60: Information added and changed for the More Media page

6. Interior 3D models embedded from URL saved in database.
7. YouTube video of climb embedded.

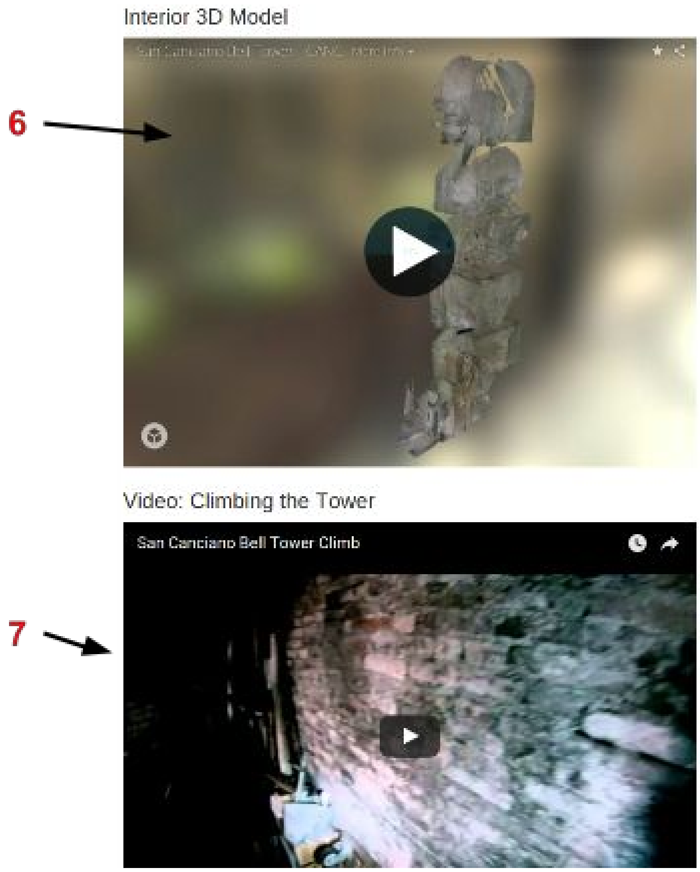

Figure 61: Shaft model and shaft climb video added to More Media page

8. Belfry model embedded into page from stored URL in database.

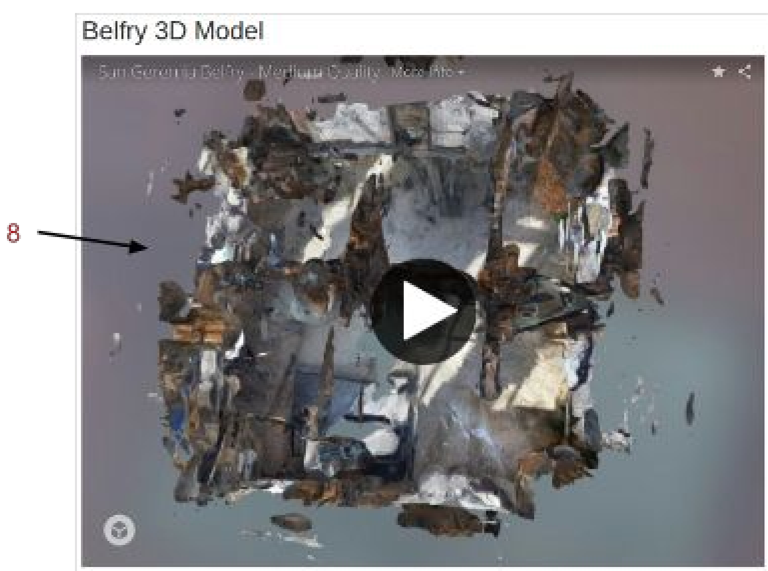

Figure 62: 3D model of Belfry embedded onto page.

9. Audio for the bell chorus embedded from database URL. The chorus was simply the sound of the bells when they were rung on schedule.
10. Audio can be downloaded for use as a ringtone.
11. Bell's Venipedia article link included.
12. Audio for each bell embedded in player.
13. 3D model of bell

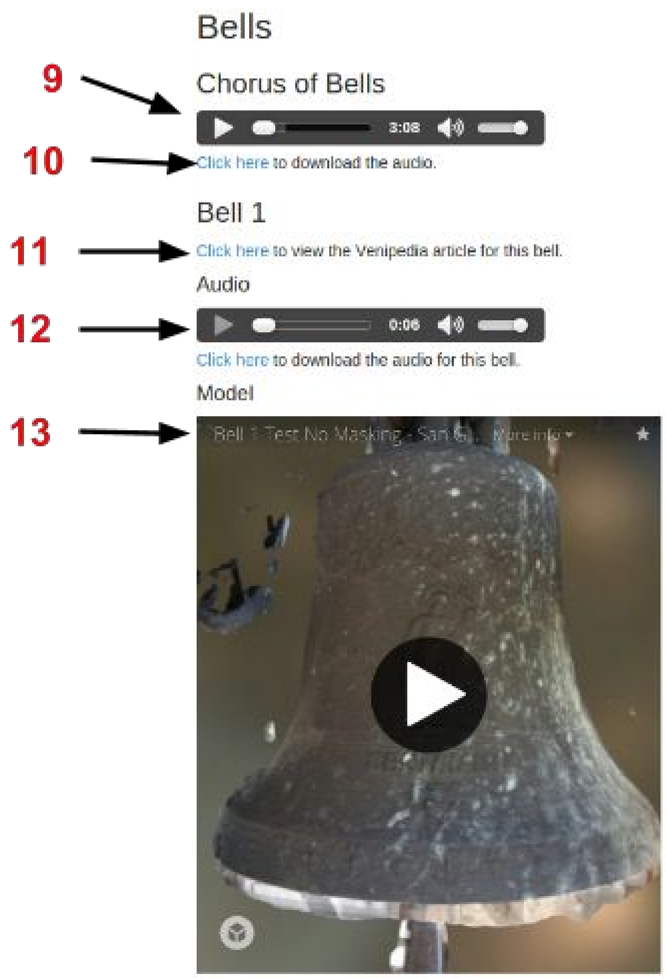

Figure 63: Chorus audio, bell Venipedia link, bell audio, and bell model

14. Link to videos and photographs of bell tower stored in Google Drive.
15. Pages from book on this particular bell tower embedded into page.

16. Link to bell tower's Venipedia page
17. Data table of information about bell tower

Figure 64: More Data section including link to album, data from book, link to Venipedia, and table of information

The modifications allow for far easier navigation of the towers and bells on the Internet. Venipedia users can now browse the information on the bell towers and, for the first time, click on pictures to see them full size. They are able to access the bells application for the bell tower from Venipedia and view all the 3D models of the tower, a view from the belfry, and listen to the audio collected for the bells. Inscriptions and decorations on the bell can be explored, and information stored on Venipedia for each bell is reachable. A link to data collected by other experts is included on these pages. In all, we have achieved an interactive experience which allows the bells and towers to be explored like never before.

Development of the application was relatively straightforward. Using data stored in the database allows layers to be color coded very easily, and relying on external data streams instead of local storage provides greater modularity and generalization. The panorama experience, though, needs some improvement. The original viewer employed a Google Streetview API, and when the site was tested, the views were broken. Minelli attempted to correct the errors but to no avail. A quicker solution was to embed the image preview and allow a user to scroll left and right. This loads very quickly and is supplied through the database, so updates to the information are easy. In addition, allowing a user to see the full resolution image lessens the criticality of the interface. While the tower data is fully displayed, it would be nicer to make the web page more interactive to reduce the amount of scrolling to see content. In all, the app allows a technical user interested in particular aspects of the bell to access such items easily and reach databanks of photographs and videos collected by the team. Casual users of the app are able to browse interesting information and engage themselves with the material.

4.2.3 Cartography Application Additions

The cartography application was modified to accurately display, on the first four archaic maps of Venice, the 20 bell towers that we visited. In past years the cartography application only had bell towers on the 1500 Jacopo de 'Barbari map, and out of these only a few were correctly named and had an active Venipedia link associated with it. We successfully identified all the bell towers that we visited in Cannaregio and the Northern Venetian Lagoon and attached each one's respective Venipedia link with our ascended survey data. In addition to these 20 towers, we were also able to identify 55 other bell towers within Venice. Once we added our visited 20 bell towers and the additional 55 bell towers to the 1500 Jacopo de 'Barbari map, we added them to the other 3 cartography maps. An example of the 1696 Giovanni Merlo map with the bell towers highlighted in green is seen in Figure 65.

Figure 65: 1696 Giovanni Merlo map with highlighted bell towers.

4.3 Creating Outlines for Future Preservation & Public Support

Public support and funding will help keep the towers preserved. A few initial ideas to promote public awareness and raise money included advertisements and collection boxes, sales of bell ring tones, and implementation of tourist events around the bell towers as explained in section 3.3.

Not many people are aware of the declining state of bell towers, and with posters summoning a call to action, locals and tourists may feel compelled to offer support. The posters would be made specific to each tower including details about the how the bells are degrading, percents about the state of the bells and their clappers, and the current size of the skid marks. As can be seen in Figure 66, on the right hand side, the bystander could access the newly updated application, find the location of the donation box for the bell tower fund, and see where the merchandise for the bell towers would be located. This can be easily created and mass produced at a low cost.

Figure 66: Example of a poster displaying the need for funding to preserve the bells of San Canciano.

Requesting voluntary donations in a collection box would be one obvious method of obtaining funds for preservation and conservation. These boxes can easily be mounted on the walls of the all of Venetian towers or the neighboring church to represent a reminder that maintenance is always needed. All donations received from each tower would be pooled in a bell tower fund to be governed by a committee. They would be able to determine what tower needs a certain amount of funding to make the restoration necessary to preserve the tower. However, each church already has multiple collection boxes inside, whether it is to light a candle, to donate for a specific alter, or to upkeep the church in general. Adding another box may detract from the church's purpose of collecting funds for restoration. A positive spin on this would be that when a certain amount is donated to the bell tower or bells, the donor would receive a code for a ringtone or choice of a postcard at the front desk area of the church where the entrance fee is paid. With this idea, it will not seem like the person is purchasing merchandise, but rather donating to help a cause and being rewarded.

When the towers are restored to their original state, the city of Venice could use them as landmarks for guided or self audio guided tours. Tourists would be excited to learn about the architects, purposes of the towers, and past events which have influenced the city through a path of linked bell towers around the lagoon. Today, if any towers were to go public immediately, the only acceptable tower from an accessibility, condition and safety perspective was La Madonna dell'Orto. All of its ramps were intact and there was both natural and artificial lighting throughout the tower. Once arriving in the belfry, there was enough room for 15 people to comfortably fit and there were no concerns about ducking under the bells. Determination of a complete tour route would have to be established once all towers have been visited. This is important because a first hand experience going up into a tower has more weight than preset values indicating condition or accessibility. With the assistance of historical committees such as UNESCO and WHC, these tours could be advertized exponentially. If the tour only focuses on bell towers and is unsuccessful, a small number of towers could be chosen based on their rating to be added to current landmark tours that Venice tourism offices already have in place.

Creating merchandise is another method of raising funds for the bells and bell towers. A few brainstormed ideas were to create various ringtones using the Venetian bells and market keychains of towers commonly found in the tourist shops of Venice. During the days and nights, different chimes of towers can be heard from locations nearby. If one wishes to hear the sounds of a particular bell through its use as an alarm sound or ringtone, it could be purchased for a small fee or, as stated above, it could serve as a reward for the donor. Ringtones can easily be made from the collected bell sounds and would be available on a global scale.

Keychains are always found in the tourist shops in Venice and would give the tourist an opportunity to remember their trip to Venice each time they pull out their keys. After weighing the pros and cons of the possible merchandise to further pursue, it was determined that creating keychains of bell tower images would be the most beneficial to fundraise for the preservation of the bells and bell towers. Keychains were chosen to pursue because they are universal to all ages and sexes and common souvenirs to purchase on vacation. To obtain information about the ordering process of these keychains, a search was conducted to find the best manufacturing and supplier source. Zazzle, an online customizable multi-product company, had the best deal to order from. As seen in Figure 67, if an order of 500 keychains were placed, the price per single unit is €2,16 and the standard 5-12 day shipping cost to Venice would be €22,95. This would total to €1.102,95, and to reach the break-even point, each keychain would need to be sold at €2,21.[86] If each key chain retailed at €4,00, a profit of €1,80 would be made. These keychains would be featured at the towers where public access was granted as well as any of the local tourism retail shops. Additionally, it would be important to advertized the keychains as a reward for donating at the public tower sites to preserve the towers. With this being said, consumers may donate an extra €1,00 instead (a total donation price of €5,00), thus increasing preservation funding. Another way to outsource this product would be through the Bells Application if it becomes a popular site visited by many people across the globe. The application could also feature the ability for users to donate directly through PayPal to towers on the map interface.

Figure 67: Order summary for possible development of keychains for preservation fund[87]

In order to ensure the bells and bell towers in Venice are not left in disrepair, a committee should be formed which seeks to establish accountability for the preservation of the bells and towers. This committee's responsibilities would include conducting surveys and studies, maintaining directories of critical contacts, organizing efforts for restoration, funneling available resources, and lobbying for preservation of the bells and bell towers. There are many groups which are involved in preservation already, but by uniting their efforts, a greater impact can be made. Members should include the church priests, expert campanologists, historical societies, and other research parties such as the Venice Project Center. Together, they would have the

[86] "Button Key Chain." 2015.
[87] "Button Key Chain." 2015.

means and expertise to properly analyze the bells and towers and create a sustainable plan to ensure the towers do not decay over time but rather steadily improve.

4.3.1 Alternative Use

Venetians and travelers could use towers as observatories, sprinkler stations, or venues for public entertainment, which would raise awareness of them, bring in possible revenue, and create a constant need to maintain them.

- Being closer to the sky and above the street haze, people interested in investigating terrestrial or celestial events in addition to constellations could enjoy trips to the belfries. Although the bell towers of Venice would be perfect locations to set up and establish such viewing stations, it would be difficult to construct an observatory. After our first-hand experience in belfries, we learned that many of the windows have metal grates over them and this would make using telescopes or other equipment difficult. Additionally, if high powered telescopes were permanently installed, this would further make this idea expensive to pursue. With that said, tickets to the top of these towers would have to be priced at an expensive rate to make up for the money spent on renovations for this project as well as the equipment purchased. If this idea were to be installed in the future, the towers of La Madonna dell’Orto, Sant'Alvise or Santi Apostoli had the most promising tower ratings. La Madonna dell’Orto was chosen because it is on the northwestern coast of Venice by the water and away from other tall buildings. Rated as a 20/20 from Figure 44, its ramps and landings are suitable for visitors to climb and the belfry is clean, very large, and the bells are high off the ground. Likewise, Sant’Alvise and Santi Apostoli had large belfries areas, acceptable stability, and good conditions for the overall landings and staircases. However, the belfries of both towers had metal beams for support systems which crossed each other and made it difficult to allow for guest. If a new support structure were to be put in place, these two towers would be the next ones to be recommended to turn into observatories.

- A less interactive use of the bell towers might be using them as weather stations[88] or an All-Sky camera network.[89] Weather is always changing and impacts daily life in Venice. A one-inch outer diameter corrosion-resistant aluminum tubing device must be used for the basis of the weather station's lightning rod. Most towers already have lightning rods and it can be adjusted and mounted using anchor bolts and a cable tie kit. This device can record wind speed and direction, temperature, humidity, precipitation, and solar radiation. Alternatively, an All-Sky camera is a 190-degree cellular fisheye projection. This technology allows for crystal clear video of the sky, both day and night. An example from Kind of Weather Observing Station (KWOS) in Scandriglia, Italy can be seen in Figure 68.

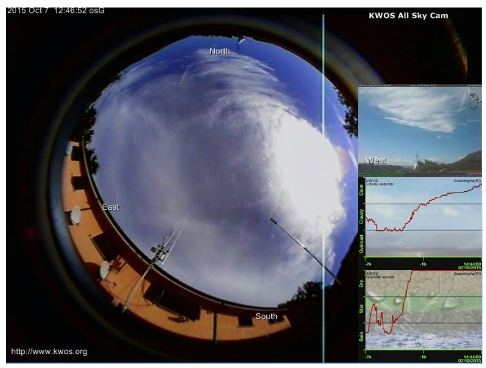

Figure 68: Image of the sky from Scandriglia, Italy showing all cardinal directions as well as a forecast and cloud formation over a period of twenty four hours[90]

With this camera one can view astronomical or terrestrial images or even use it as a weathercasting device, displaying cloud formation and precipitation. It could also be used as a supporting video feed for pilots and airport ground crews. These cameras could be setup in place of observatories and this would allow people to observe the sky from the comforts of their own home. 118 of these cameras would not be needed, as they are expensive, around €1.000 each, and the towers are relatively close together. In the future, a strategically laid out grid of cameras could be created to include one in each sestriere as

[88] "UT20 and UT30 Universal Towers." 1993.
[89] "Moonglow Technologies - All Sky Cam." 2008.
[90] "All Sky Cam.com - KWOS Scandriglia, ITALY." 2015.

well as a few spread out among the islands. For the current scope of this project, of the towers that were visited, the recommended locations for these cameras would be San Canciano, San Geremia, San Donato (Murano), and Santa Maria Assunta (Torcello) as seen in Figure 69. This is because weathervanes are already present and the cameras would be mounted with ease.

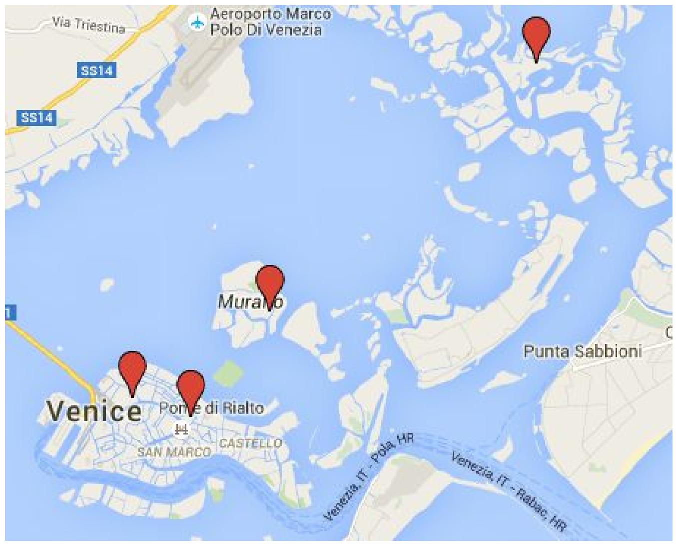

Figure 69: Possible map of AllSky Camera locations spaced throughout the lagoon[91]

- Another reasonable and relatively easy reuse for the 118 towers would be to turn them into sprinkler stations. A system of discrete water lines would lead from the foundation up the side of the shaft and the nozzle of the hose would be placed at the top of the tower or belfry depending on the height. The sprinklers would be aimed in the direction of the church roofs in case of a fire. The construction of this idea may take time intensive labor and a great deal of money, but it is rather difficult to manager a fire with the tourists covering the streets of Venice and this alternative use would be beneficial in preserving the church and the valuable artifacts inside of it. All towers would be considered for the expansion of this alternative use as the effects of a fire could be damaging to the surrounding buildings.

[91]"Venice, IT." Map. Google Maps. Google, 11 Dec 2015. Web. 11 Dec 2015.

- Since the towers of Venice are all relatively close together, the best method of capturing the attention of the public would be to orchestrate a bell concert that can be heard from a large plaza or square. The closeness of towers and the size of the plaza would have to be compared in order to address safety concerns and ensure success for the expansion of this idea. These concerts would have to be well thought out and carefully planned, but from our seven week experience in Venice, we would not be able to properly determine the location at which these concerts are held. Unfortunately all of the bell towers located in the sestiere of Cannaregio were too far from each other to hold a concert, as seen in Figure 70.

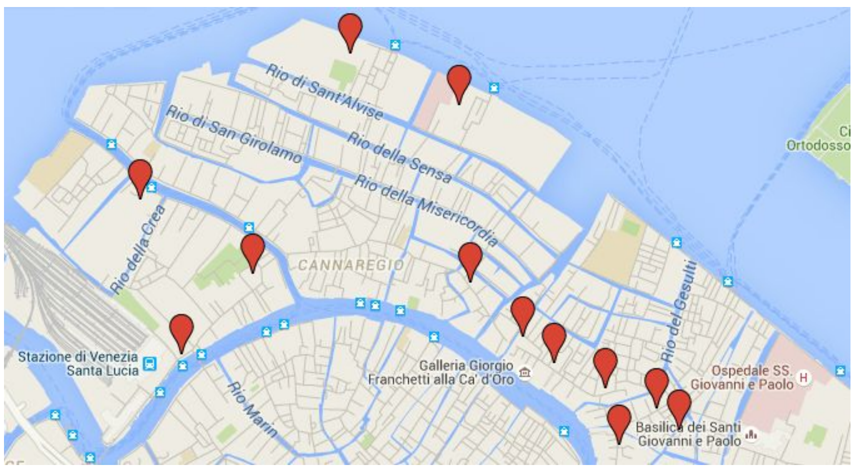

Figure 70: Location of all Cannaregio Towers prove they are too spaced out and not close enough to one campo.[92]

Venetians and tourists would be able to enjoy to the musical chorus from the bells as they are synchronized together to chime on special occasions or monthly events. This use of the bells would be in supportive of their original purpose and would require the constant upkeep of the bells continuously. The implementation of these ideas and strategies could only move forward with support from the city and church officials along with future bell and bell tower evaluations.

[92]"Venice, IT." Map. Google Maps. Google, 11 Dec 2015. Web. 11 Dec 2015.

5. Conclusion and Recommendations

In this project, we conducted 20 complete surveys of bells towers in the Vicariate of Cannaregio and the northern lagoon area. There remain 98 bell towers in Venice that need to be surveyed by the Venice Project Center. Future studies on the bells and bell towers may use our data collection tools and modified user applications to guide their work. In doing weeks of field world, we expanded our knowledge of bells and came to value them, realizing the vital role they play in the history and culture of Venice.

Our survey data was organized and documented in spreadsheets, panoramas, 3D bell models, 3D belfry models, 3D shaft models, ascended videos, and audio recordings of individual bells. Over 80 3D models were created, more than 60 videos uploaded to YouTube, and greater than 50 audio recordings were collected during the project. This data is now available to the public and to researchers at bells.veniceprojectcenter.org and in wiki pages on the Venipedia site. In Venipedia, the general information pages were expanded and refined. The template generating the Venipedia Bell Towers pages was edited to reduce clutter of absent data and allow photographs to be opened at full resolution. Users may now access the tower data documented from other professional sources and navigate to information in the Bells Application. In the Bells Application, a new approach generated by information in the CK Database was applied to allow data additions to be easy and the app to automatically update with new information. 3D models, videos, audio, and reports were embedded into the page. The audio and video the team collected could also be reached from the tower pages, and new ways to visualize the bell tower data revitalized the main map interface. Based on this work, we came up with many recommendations for future VPC researchers.

If we were to recommend one tower be pushed for public access it would be La Madonna dell'Orto. The tower had very promising levels of accessibility, a clean and well kept belfry, and one of the best views of any tower in the city. There were no noticeable major safety or access concerns. An addition of a screen or net to the upper balcony would allow the public to visit. Funds from bell tower entries could help support any future maintenance of the structure and the bells. This tower scored highest amongst the 20 bell towers that the team studied, and we believe it could be only a few small steps away from competing with San Marco or San Giorgio.

A tower that we would recommend immediate restoration and renovations to is Santa Caterina e San Pietro. The tower is in poor condition, with crumbling stairs of rotting wood and a serious bird infestation. The belfry was covered in guano and had a large amount of plant life growing throughout the belfry, creating conditions for further erosion of the structure. The landings had many holes, cracks, and decaying supports from being left alone to the elements. The tight stairway also makes maneuvering through the shaft difficult for future caretakers. This belfry consistently scored low in all of our rating categories.

Overall, however, we found that in terms of conditions, 35% of bell towers that we visited were marked as excellent for landing condition but only 24% were marked as excellent for belfry conditions. We also able to conclude in terms of accessibility 29% of bell towers had excellent staircase accessibility. Specific to belfry accessibility, only 12% of the towers we surveyed could be deemed excellent.

Creating merchandise is another method of raising funds for the bells and bell towers, which would ultimately lead to preservation. We worked to capture the public's attention by designing informative posters about specific bell towers, we produced a Computer Aided Design (CAD) model of a belltower that can be 3D printed and turned into a donation box for bell tower. We drafted a merchandise plan of keychains specifically for La Madonna dell'Orto. It is our hope that future researches will continue to advance and develop these plans for funding and preservation of these historic structures

5.1 Recommendations for Towers

The towers with severe vibrations readings, specifically SS Apostoli and San Angelo, should be studied to determine if there is imminent danger caused by ringing the bells. Certainly for San Angelo, bell ringing should be shortened immediately. During the survey, the bells swung continually for around five minutes. This caused undue stress on the tower, and such a long period of time was not necessary. The church should be contacted with this information in an effort to reduce the possibility of this tower collapsing. In the case of SS Apostoli, further testing should be conducted to determine whether these large stresses are significantly impacting the structure. Perhaps a vibration dampening system similar to the one present at San Pietro, Figure 71, could be used to lessen the impact felt by the structure. Unfortunately, the bells did not ring at San Pietro, so the effectivity of the vibration dampening could not be determined.

Figure 71: Vibration dampening device at S. Pietro

Another way in which vibrations and forces can be lessened on the tower is by reducing the forces produced by the bells themselves. Through installing counter-rotating masses above each bell, the moment generated during the swing is counteracted by the opposite rotating mass above the bell. This would reduce the moment transferred from the frame to the tower and should improve tower sway. A way to illustrate this phenomenon would be for a person quickly lifting a heavy bucket with one arm on their side. It would be difficult for them to remain standing perfectly straight; they would tend to lean toward one side as they began lifting the bucket. However, if they lifted an equally weighted bucket with the other hand, they could remain straight since the forces would be balanced. This is similar to how the bell tower would behave: when a bell swings, the tower lurches slightly as it feels the effect of the moving bell. However, with countermasses mounted, this effect would nearly be eliminated. This approach should be further researched to determine costs and feasibility, such as whether the counter rotating masses could fit in the sometimes limited space in the belfries.

Bell towers that have wooden frames should be protected such that restoration efforts will not replace the wooden structures with metal. As discussed previously, wood is superior to metal in belfries in terms of vibration dampening and bell acoustics. These 8 bell towers are the ones which currently have wooden frames, Table 6:

Bell Tower	Frame Material
San Angelo - ANGE	Wood
Santa Maria Assunta - ASST	Wood
San Canciano - CANC	Wood
San Donato - DONA	Wood
Sant' Eurosia - EROS	Wood
I Miracoli - MIRA	Wood
La Madonna dell'Orto - ORTO	Wood
Santa Sofia - SOFI	Wood

Table 6: Bell towers with wooden belfry frames

However, these 10 bell towers have metal frames, Table 7:

Bell Tower Code	Frame Material
Sant' Alvise - ALVI	Metal
I Santi Apostoli - APOS	Metal
Santa Caterina e San Pietro - CATM	Metal
San Felice - FELI	Metal
San Geremia - GERE	Metal
San Giobbe - GIOB	Metal
San GIovanni Gristomo - GRIS	Metal
San Martino - MARB	Metal
San Pietro Martire - PIEM	Metal
Gli Scalzi - SCAL	Metal

Table 7: Towers with metal belfry frames.

Future preservation efforts should focus on determining cost for replacing the current metal frames with new wooden ones and on creating a plan for this restoration process. It is important to ensure that current wooden frames are not replaced by new metal ones. Similarly, if a tower is being renovated, the change back to wooden belfry frames should be made.

5.2 Method Recommendations

In terms of data collection, future projects could improve upon the methodology of this study significantly. One of the most difficult types of data to capture from the bell tower was the panoramic view from the tower, which was often obstructed by irremovable mesh. A way to alleviate this issue would be to move the camera outside of the mesh. This could be done by using a small tubular camera to poke through the mesh or through the use of an external quadcopter drone. In fact, using a drone to capture the exterior of the tower would also allow the tower to be properly 3D modeled through photogrammetric methods. When we attempted this from the ground, it resulted in poor quality of the top of the bell tower. However, according to ENAC, the Italian Civil Aviation Authority, it is prohibited to fly an unmanned aircraft within eight kilometers of an airport.[93] More research would be needed to see if overcoming these regulations is possible.

Another aspect of the tower data collection was the 3D models collected with the Tango Tablet. As a first generation device, it's scan quality is acceptable, but visually poor. In another year or two, future models should drastically improve model quality and allow the towers to be captured in better quality. This capture method is more desirable than photogrammetry since the construction is completed in real time and it is quicker to use the Tango than to take hundreds of still photographs and process them as we did.

Data collection on the tower structure condition could be improved as well. Cracks should be measured in a more sophisticated manner. Their length, width, and approximate depth should be recorded in the future. If long-term observations are desired, gauges should be affixed across the cracks to record crack changes over time. It would only be through measuring the growth of such cracks that analysis can be conducted on the vulnerability of the bell towers. The IMU in a smartphone was good at detecting vibrations and shocks felt in the tower, but it failed to detect swaying since that motion did not have large accelerations. It was not planned during the preparation term to measure sway, so there was no methodology present for this case.

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[93] ENAC (Ente Nazionale per L'Aviazione Civile). "MEZZI AEREI A PILOTAGGIO REMOTO." 2013.

Additionally, the team only observed one tower swaying (San Angelo) while the bells were ringing.

To better measure the acceleration of the tower when the bells are rung, more sophisticated sensing equipment is necessary. Instead of a cellular phone, a dedicated IMU's should be used that can be connected to powerful recording software. Rather than use a single IMU, a network of IMU's can be placed in various locations around the tower to determine how different parts of the building move and absorb vibration. The IMU's should be affixed to the structure using double sided tape such as 3M's VHB (Very High Bond) tape, which would prevent the IMU from shaking independently from the tower. If the IMU's were being installed in the tower permanently, they should be affixed with 5 minute epoxy. Some recommended IMU mounting locations are listed below:

- Belfry frame:
  - In middle of frame, right next to a bell
  - Along a support member
  - On the frame support before it is attached to the tower frame
- Tower:
  - In center of belfry floor under the bells
  - On a window sill
  - In the center of each landing
  - Located on the ground

Mounting IMU's on both the belfry frame and the tower itself would allow analysis to be conducted on the severity of vibrations that are transferred through the frame material. In this way, it could be verified that metal is a better carrier of seismic energy than wood and thus should not be used in the towers. By researching ways to detect tower or building sway, perhaps through the use of a pendulum hung inside of the tower, a future team would be in a better position to analyze the structural condition of bell towers. We also suggest future teams ensure their presence during ringing times to allow more complete collection of this data.

Creating the 3D models using Photoscan required lengthy processing time, even on a high end laptop computer with dual graphics cards. Furthermore, creating higher quality meshes was impossible for most bell models without having more than 16 Gigabytes (GB) of Random Access Memory (RAM). Future groups using photogrammetry should invest in a dedicated server/desktop system that meets the hardware and memory requirements for Photoscan. According to their website, about 64 GB of RAM should be included for building high quality models based on the number of photos taken for the bells.[94] A recommended advanced hardware configuration, suitable for high quality reconstruction, includes a six-core i7 processor, motherboard with 8 RAM slots and at least one PCI-E X16 slot, 8 RAM modules each of either 8GB or 4GB varieties, and a GTX 980 graphics card. Dual socket Intel Xeon configurations would make the process even faster.[95] Such hardware improvements would drastically increase the speed and quality of 3D models developed using photogrammetry, though the cost of such systems could easily exceed €1.500.

New camera systems should also be explored to see if there are faster ways to collect the photographs while in the tower. It takes time to focus on the bell for each photograph, so it is possible that with a fixed focus camera, like a GoPro, the photographing would go much faster. However, this could have the consequence of reducing the quality of the photographs. Additionally, a camera with a wider angle could capture more of the bell surface in a single shot, allowing better localization at the potential cost of reduced image quality. Future teams should conduct testing to see what camera systems produce the best tradeoff between quality and time.

In publicizing the data throughout the applications, teams should focus on streamlining the data presentation across both Venipedia and the Bells application. The CK database should be used as the repository for associating important media for each bell and bell tower since additional data added to it will automatically populate in the applications. On the main interface, a search bar feature could be added to allow a user to search for certain towers, and the map could recenter on that tower and bring up information. The More Info page in the bell tower application could use a more polished interface, such as a clickable bell tower template with popout content for each part of the tower. Venipedia bells templates and data need significantly more work. Future teams should focus on integrating all the information collected over the years into the database.

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[94] P, Alexey. (sic) "PhotoScan Memory Requirements."
[95] "System Requirements." Agisoft Downloads.

Finally, time management was a crucial point in this project. Completing twenty tower surveys was very time consuming, and the data collected at the conclusion of the project still needs further processing that will continue beyond this project. Future teams should, we suggest, continue to survey 20 towers over the course of a seven-week research stay in Venice. It took a team member, new to javascript and angular, about two and a half weeks to write the changes for the bells application and Venipedia. This is now completed, so team members would have more time to process 3D models and data collected during the survey.

With all these recommendations in mind, we are hopeful that all future researchers for the Venice Project Center can move closer to preserving the historically significant Venetian bells and bell towers.

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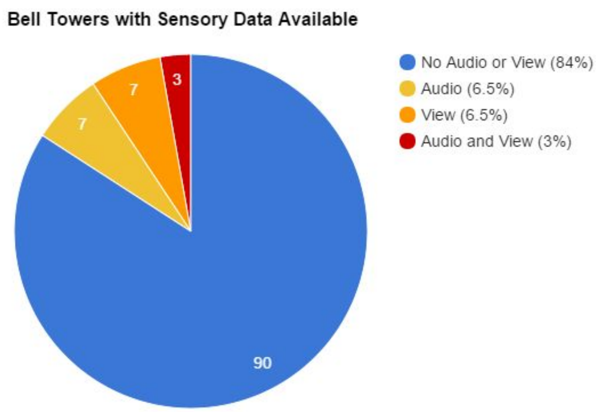
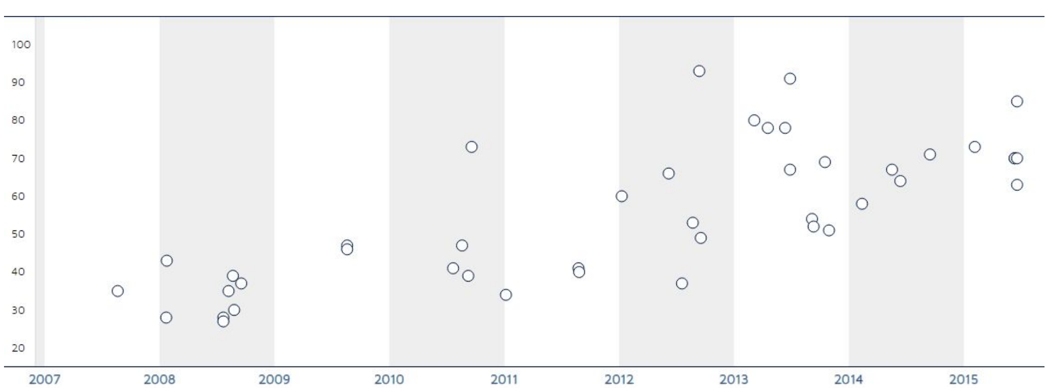
Appendix

A. Bell Tower Data Chart



Number of Bell Towers with Sensory Data in Online Bells Application[96]

B. Camera Benchmarks over Time



Camera benchmark scores over time. Benchmark measures color recognition, exposure range, and usable ISO levels[97]

[96] "Venice Bells Application."
[97] DXOMARK.

C. List of Bell Towers

Below is a list of all 118 bell towers.

Name
Sant'Alvise
La Zirada
Santa Maria degli Angeli
San Angelo
San Antonin
San Antonio
Sant'Aponal
I Santi Apostoli
I Gesuiti
Santa Maria dell'Assunzione
Santa Maria Assunta
San Barnaba
San Bartolomeo
San Marco
San Benedetto
San Boldo
S. Bonaventura Capuccine
San Canciano
I Carmini
San Cassian
Santa Caterina
S. Cosmo
La Croce
San Donato
San Giovanni Elemosinario
Sant'Elena
Santa Maria Elisabetta
Sant'Erasmo
Sant'Erosia
San Eufemia
San Giovanni Evangelista
Fava 1
Fava 2
San Felice
Santa Maria Formosa
Santa Fosca in Cannaregio
Frari
San Geremia
I Gesuati 1
I Gesuati 2
San Giorgio
San Giobbe
I Greci
San Giovanni Grisostomo
San Giuseppe
Santa Maria della Visitazione 1
Santa Maria della Visitazione 2
I Mendicanti
San Luca
Santa Maria Maggiore
San Martino
San Marcuola
Santa Margherita
San Martino
San Marziale
Maria Mater Domini
San Nicolo dei Mendicoli
San Michele
I Miracoli
San Moisè
San Nicolò
Ognissanti
Ognissanti di Pellestrina
San Giacomo dell'Orio
La Madonna dell'Orto
San Pantalon
San Francesco di Paula
San Pietro
San Pietro Martire
San Pietro di Castello
San Polo
Anzolo Rafael 1
Anzolo Rafael 2
I Rendentore 1
I Rendentore 2
Santa Caterina
San Rocco
Le Romite
La Salute 1
La Salute 2
San Salvador
San Samuele
Gli Scalzi
San Sebastiano
San Silvestro
San Simeon Grando
San Simeon Piccolo
San Lio
Santa Sofia
San Stae
San Stefano
Santo Stefano di Murano
Le Terese
I Tolentini
Torre dei Baini
Santissima Trinità
San Trovaso
La Misericordia
S. Vidal
La Vigna
Santa Maria della Visitazione
San Zaccaria
San Zandegola
San Zaninovo
Le Zitelle 1
Le Zitelle 2
San Zulian

D. Bell Tower Exterior Data Fields

Bell_Tower_ID
name
Number of Bells
Bell_Tower_Parts (Foundation, Shaft, B
Tower Height (m)
Material
Exterior Block Height (cm)
Exterior Block Width (cm)
Exterior Block Depth (cm)
Visibility Front
Visibility Right
Visibility Back
Visibility Left
Visibility Distance Front
Visibility Distance Right
Visibility Distance Back
Visibility Distance Left
Exterior Tower Notes Front
Exterior Tower Notes Right
Exterior Tower Notes Back
Exterior Tower Notes Left
Connected to Front
Connected to Right
Connected to Back
Connected to Left
Length_attached_percentage Front
Length_attached_percentage Right
Length_attached_percentage Back
Length_attached_percentage Left
Num_Plants Front
Num_Plants Right
Num_Plants Back
Num_Plants Left
Num_art_pieces Front
Num_art_pieces Right
Num_art_pieces Back
Num_art_pieces Left
Num_cracks_holes Front
Num_cracks_holes Right
Num_cracks_holes Back
Num_cracks_holes Left
Num_brick_colors Front
Num_brick_colors Right
Num_brick_colors Back
Num_brick_colors Left
Num_ties_bands Front
Num_ties_bands Right
Num_ties_bands Back
Num_ties_bands Left
Window Number Front
Window Number Right
Window Number Back
Window Number Left
Blocked Window Number Front
Blocked Window Number Right
Block Window Number Back
Blocked Window Number Left
Barred Window Number Front
Barred Window Number Right
Barred Window Number Back
Barred Window Number Left
Meshed Window Number Front
Meshed Window Number Right
Meshed Window Number Back
Meshed Window Number Left
Restoration Visible Front
Restoration Visible Right
Restoration Visible Back
Restoration Visible Left
Orientation (degrees) Front
Orientation (degrees) Right
Orientation (degrees) Back
Orientation (degrees) Left
inclination_rating
inclination_direction
inclination_calculated
plumb_line_length
plumb_bob_distance
overhang_calculated (m)
public_access
Accessibility Front
Accessibility Right
Accessibility Back
Accessibility Left
Exterior Door Front
Exterior Door Right
Exterior Door Back
Exterior Door Left
Exterior Door Height (cm)
Exterior Door Width (cm)
Clock Side
Clock Working?
Clock_Mechanism_Landing
number_lessene
number_sections
Arches Front
Arches Right
Arches Back
Arches Left
No. Exterior Inscriptions
Inscription
Inscription Description
avg_inscription_legability
num_decorations
Decoration_description
Decoration_condition
belfry_style
drum_type
Balustrade
attic
cross
weathervane
lightning_rod
finial
finial_type
finial_description
connected_wire
connected_unclear
import_notes

E. Bell Tower Interior Data Fields

Bell_Tower_ID
Landings
Landing Material
Landing Sturdiness
Landing Cleanliness
Landing Length F-B (cm)
Landing Width R-L (cm)
Landing Height to ceiling (cm)
Ramp?
Stairs?
Staircase Side
Staircase Material
Number of Steps
No. of Bad Steps
Staircase Cleanliness
Staircase Sturdiness
Railing
Block Height (cm)
Block Width (cm)
Block Depth (cm)
Wall Material
Wall Thickness
Window Total Number
Window Side
Window Height (cm)
Window Width (cm)
Window Depth (cm)
Interior Door Front
Interior Door Right
Interior Door Back
Interior Door Left
Interior Door Height (cm)
Interior Door Width (cm)
Interior Door Depth (cm)
Interior Door Notes
Restoration Sides
Number of Ties and Bands Front
Number of Ties and Bands Right
Number of ties and Bands Back
Numer of Ties and Bands Left
Cracks and Holes Front
Cracks and Holes Right
Cracks and Holes Back
Cracks and Holes Left
Damage Stone Front
Damage Stone Right
Damage Stone Back
Damage Stone Left
Misaligned Brick Front
Misaligned Brick Right
Misaligned Brick Back
Misaligned Brick Left
Natural Lighting
Artificial Lighting
Notes
Frame Type
Frame Restoration
Frame Material
Frame missing_screws_bolts
Frame rust
Frame cracks
Frame cleanliness
Frame warping
Frame dents
Frame Overall_condition
Frame Notes
num_internal_inscriptions
internal_transcription
num_internal_decorations
internal_decoration_locations
Internal_decoration_description
internal_average_legability
internal_average_conservation

F. Bell Tower Extraneous Information Fields

Bell_Tower_ID	time_open_2	[CODICE]_ext_top
Church	significant_history	[CODICE]_ext_skyshot
Common Name	tower_style	[CODICE]_ext_F
Last Visited	construction_year	[CODICE]_ext_L
Proprietor	repair_year	[CODICE]_ext_B
Danger_Zone	repair_description	[CODICE]_ext_R
Number of Bells	Renovation_Restoration_years	[CODICE]_int_landing_ground
longitude	Renovation_Restoration_description	[CODICE]_int_landing_belfry
latitude	architecture	[CODICE]_int_landing_attic
Sestiere	architect	[CODICE]_machine
time_open_1	[CODICE]_ext_tower	[CODICE]CC_1

G. Bell Information Fields

Bell_Tower_ID	Crown Inscription Back	ringing_method	[BellCode]_I
name	Crown Inscription Left	Automatic	
Sestiere	Body Inscription Front	Manual	
bell_ID	Body Inscription Right	working	
Musical Note	Body Inscription Back	first_casting	
Frequency (Hz)	Body Inscription Left	second_casting	
Ringing Times Monday	Lip Inscription Front	Historic_info.	
Ringing Times Tuesday	Lip Inscription Right	cleanliness	
Ringing Times Wednesday	Lip Inscription Back	discoloration	
Ringing Times Thursday	Lip Inscription Left	Clapper Rust	
Ringing Times Friday	clapper_description	decorations	
Ringing Times Saturday	belt_description	inscriptions	
Ringing Times Sunday	stock_description	belt	
Crown Engraving Front	conservation_state	overall_condition	
Crown Engraving Right	Skidmark 1 Side	foundry	
Crown Engraving Back	Skidmark 1 Left (cm)	Place of Casting	
Crown Engraving Left	Skidmark 1 Right (cm)	diameter (cm)	
Body Engraving Front	Skidmark 2 Side	height_internal (cm)	
Body Engraving Right	Skidmark 2 Left (cm)	height_ground (cm)	
Body Engraving Back	Skidmark 2 Right (cm)	[BellCode]_F	
Body Engraving Left	chips	[BellCode]_L	
Lip Engraving Front	safety_cable	[BellCode]_B	
Lip Engraving Right	chiming_frequency	[BellCode]_R	
Lip Engraving Back	cracked_side	[BellCode]_F_dec	
Lip Engraving Left	swing-direction	[BellCode]_L_dec	
Crown Inscription Front	hammer_side	[BellCode]_B_dec	
Crown Inscription Right	reason_not_rung	[BellCode]_R_dec	

H. Trigonometric Method For Estimation of Tower Lengths

Calculating Bell Tower Height:

Given X = distance from bell tower

Given Y = Height of Tower above persons eyeline

Given theta = Angle of elevation from observer's eyes to Tower.

Given H = person's eye height

Given T = Total tower height

Tan(angle) = Y / X

Y= (tan(angle) * X)

T = Y + H

Calculating Tower Side Length:

Given X = distance from bell tower

Given Theta = angle formed from observer's location to opposite corner of bell tower side being measured

Given Y = Length of desired side to be measured.

Y= (tan(angle) * X)

Calculating Tower Tilt Angle:

Given X = Distance string hangs from tower

Given Y = Length of string.

Tilt of tower = Arctan(Y/X)

Calculating tilt with pixels:

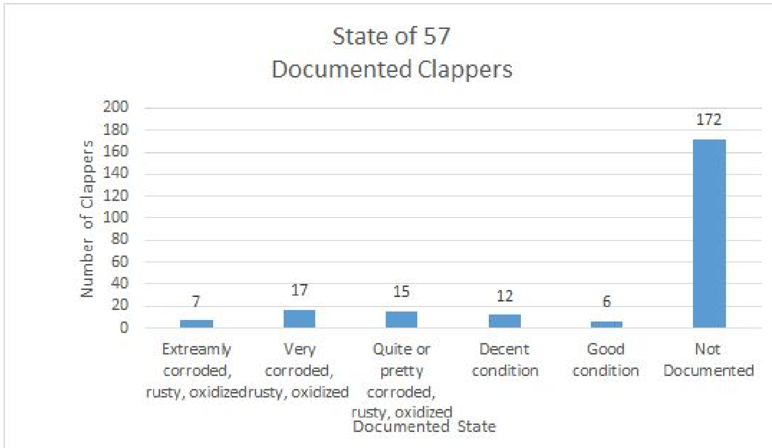
Given X1= coordinate of farthest extending base pixel in the X axis.

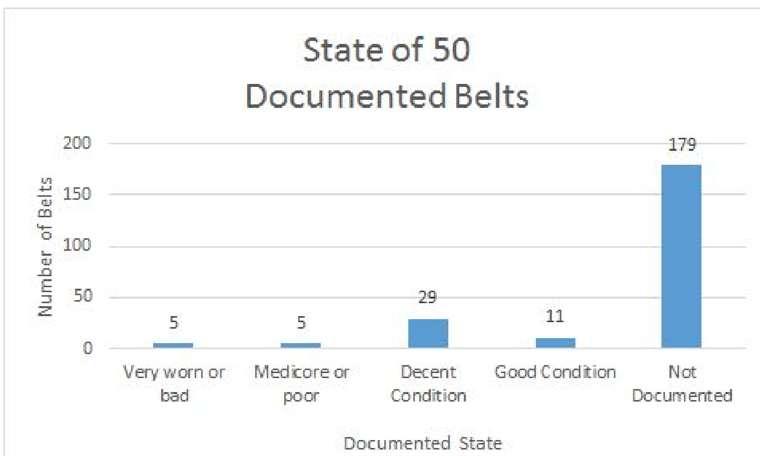
Given X2 = coordinate of farthest extending pixel in the X axis of the belfry

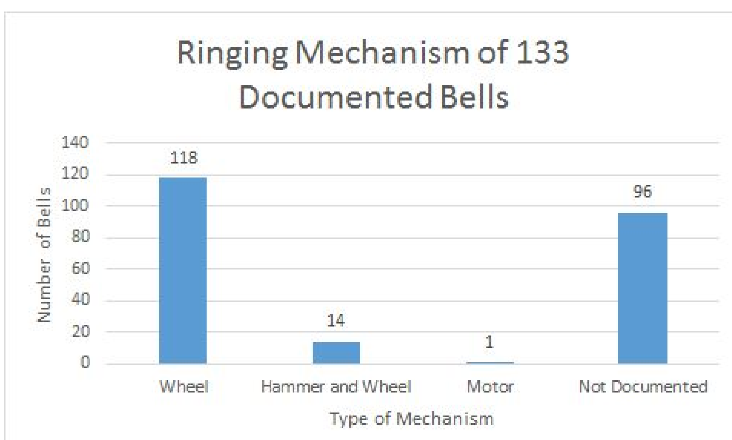
Given Y = Difference of the Y coordinates of X1 and X2

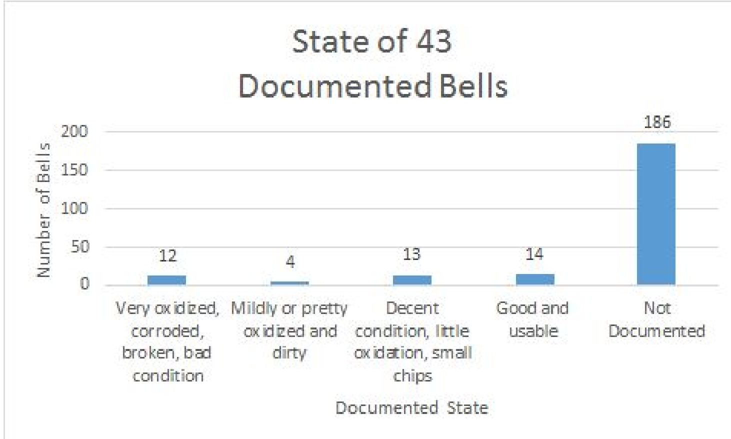
Tilt of tower = Arctan (Y/X2-X1)

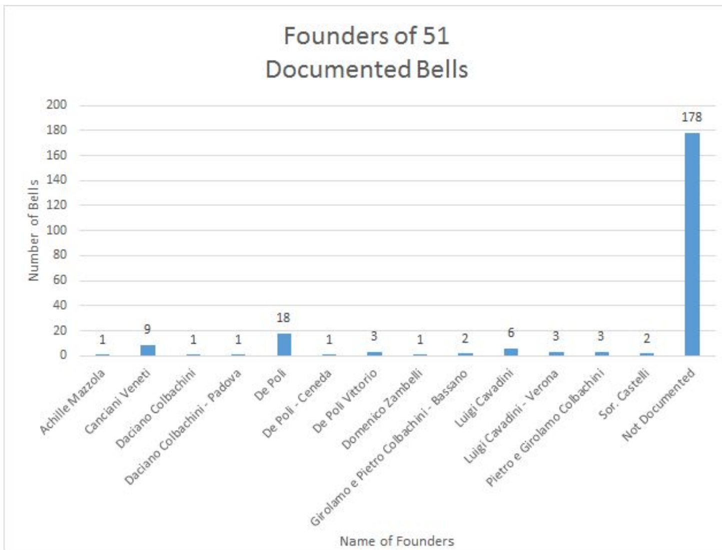
I. Bell Data Compilation from 2013



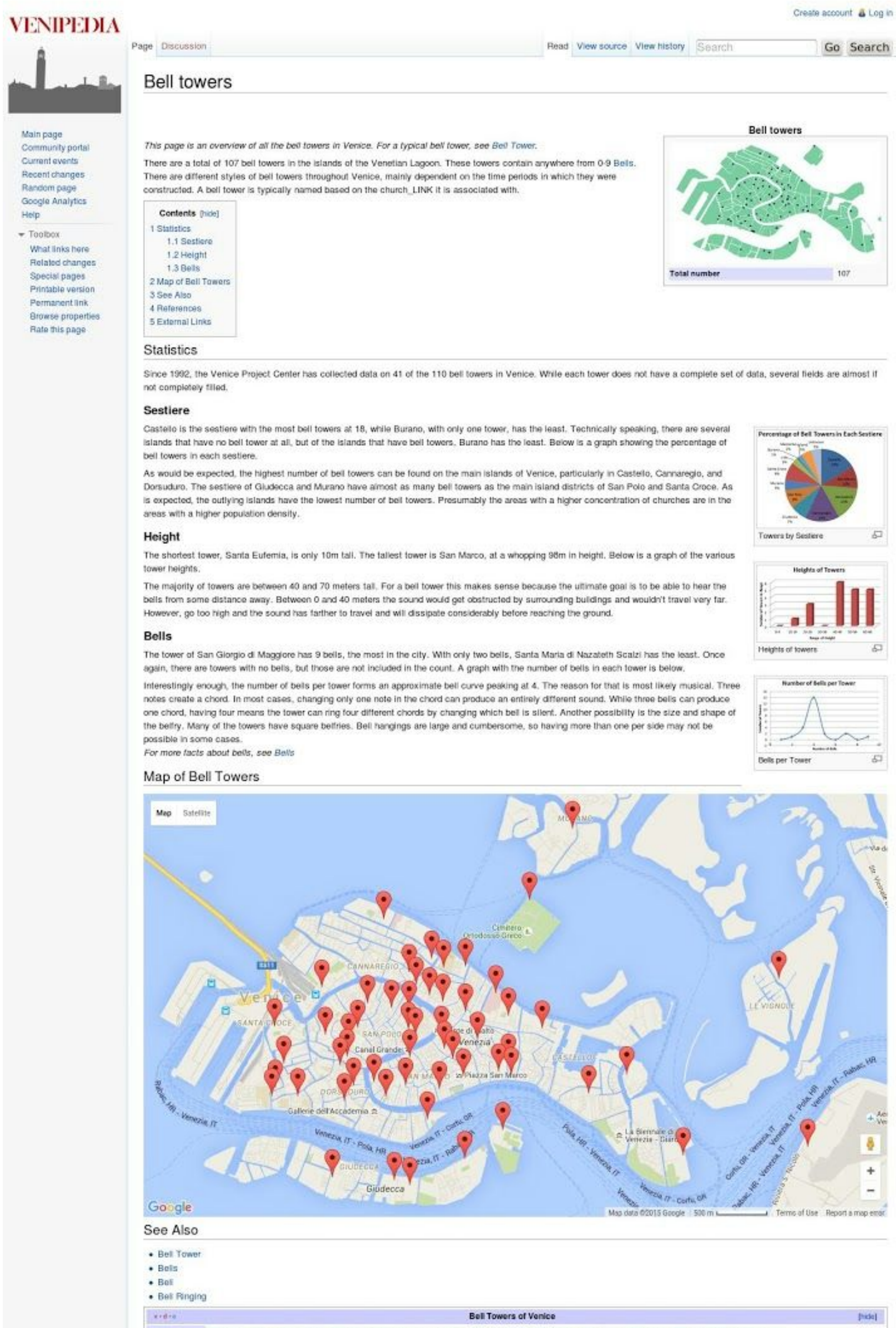





State of 43
Documented Bells
Number of Bells
200
150
100
50
0
12
4
13
14
186
Very oxidized, corroded, broken, bad condition
Mildly or pretty oxidized and dirty
Decent condition, little oxidation, small chips
Good and usable
Not Documented
Documented State


Founders of 51
Documented Bells
Number of Bells
200
180
160
140
120
100
80
60
40
20
0
1
9
1
1
18
1
3
1
2
6
3
3
2
178
Achille Mazzola
Canciani Veneti
Daciano Colbachini
Daciano Colbachini - Padova
De Poli
De Poli - Ceneda
De Poli Vittorio
Domenico Zambelli
Girolamo e Pietro Colbachini - Bassano
Luigi Cavadini
Luigi Cavadini - Verona
Pietro e Girolamo Colbachini
Sor. Castelli
Not Documented
Name of Founders

J. Venipedia General Pages



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Bell tower

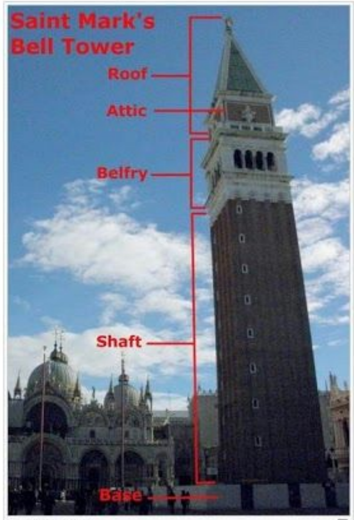
This article contains information about a typical Venetian bell tower. For an overview of all the bell towers, see Bell towers.

A Venetian bell tower, known in Italian as *campanile*, is used to house many Bells. A bell tower is typically named based on the church it is associated with. Over many centuries the design and aesthetics have changed, but their sole purpose, to house and protect bells while enhancing their sound, remains unchanged.

Contents [hide]

Bell Tower Structure of a Campanile

There are four main components to the structure of a bell tower: base, shaft, belfry, and roof. Each of these contributes to the overall style and integrity of the tower.



Bell tower structure

Base

The base provides the main support of the tower by embedding its foundation into the rock beneath it. Its purpose maintain the structural integrity of the tower. The base contains tensioning supports which are driven into the ground as well as other stability enhancing measures. The walls at the base of the tower are often thicker and made of non-porous materials compared to those at the top. These materials are used so that it is resistant to salt water due to flooding and heavy enough to withstand the pressure from the weight of the tower.

Shaft

The shaft is the part that contributes to the height of the tower and contains stairs, ramps, and landings leading to the belfry. It is usually constructed of brick and mortar, which is varied in strength based on the year that it was constructed because the method for making brick was also changing over time. In addition, to provide the tower with greater flexibility and support, some tower shafts were built using metal rods.

Belfry

The belfry, located above the shaft, contains the bells and a type of landing. On the exterior, it is the most ornate part of the tower, built using brick and other types of stone or clay. Typically, there are windows or arched openings that allow for the sound of the bells to be heard and occasionally netting to keep pigeons from entering. The bells are hung from the top of the belfry using the traditional A and H frame supports with wood, although some newer towers use metal.

Roof

Above the belfry there may be an attic which provides additional storage or access to the top of the tower for maintenance. There may also be a balustrade, or a balcony with a railing that runs around the outside of the attic. This is usually accessible from the attic, so that one may enjoy a more expansive view and have additional access to the roof. To get to the attic, there is either a ladder or stairway.

The spire is the structure on top of the church roof that tapers up to a point and varies depending on the tower, having many shapes: conical, pyramidal, bulbous, and others. On top of the spire there can also be a finial. A finial is a small decorative ornament or feature, which ranges from functional, such as a weather vane or lightning rod, to ornamental, such as a cross or statue.

Bell Tower Structure of an A vela

Common to many parts of Italy and other Romantic nations is the A vela, also known as the Roman Bell Towers. These structures are arches with bells that hang from their apex. They were very common during the age of the Roman Empire due to their ease of construction and reliability. Prior to modern material science and engineering designs, large towers were difficult to erect and maintain. For these reasons the Romans built bell arches, a structure they had mastered over centuries.

Architectural Style

Like most buildings, there are many different styles of tower architecture. Over the centuries many of the towers have seen numerous renovations resulting in overlapping styles, causing the original style to be virtually indistinguishable. Their eclectic nature reflects the city's history and the diverse ideas that evolved in Venice. Overall, bell towers contribute a great deal to the ambiance of the city.
For more information on architectural styles, see External Links.

Bell Tower Maintenance

Earthquake destruction

Cultural changes including the decline of religion and the use of modern technology, has reduced the need to ring the bells manually, and therefore resulted in people being removed from the process of maintaining those bells and their towers. For example social influences of the early 2000s swayed individuals away from the strict regulations set by the Vatican Council. The percent of Italians who attend church on a weekly basis over the course of 42 years decreased steadily over time. The graphic data was obtained through a series of cross sectional surveys that were pooled and referenced against data collected from individual churches. 1

Even in acts of preventing collapse, there are cases where the matters are simply made worse. When reinforcing towers or old masonry buildings with steel and other metals, these materials have the effect of amplifying any earthquakes and further damaging the structure because they are excellent conductors of seismic waves. 2 In the case of bell towers specifically, the rotting wooden structures that support the bells and ringing mechanisms are sometimes replaced with metal, which transfers more of the vibrations to the masonry rather than allow the wood to absorb the shock.

See Also

- Bell Towers
- Bells
- Bell
- Bell Ringing
- Church

References

1. Lagomarsino, Sergio, and Stefano Podesta. "Damage and vulnerability assessment of churches after the 2002 Molise, Italy, earthquake." Earthquake spectra 20.S1 (2004): S271-S283.
2. Vezzoni, Cristiano, and Ferruccio Biolcati-Rinaldi. "Church Attendance and Religious Change in Italy, 1968-2010: A Multilevel Analysis of Pooled Datasets." Journal for the Scientific Study of Religion: 100-18. Publication about the decline of religion in Italy from 1968-2010.

External Links

1. https://en.wikipedia.org/wiki/Architectural_style

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Bells

This page is an overview of all the bells in Venice. For a typical bell, see Bell.

Venice has 229 **bells** spread throughout the city and lagoon.

Contents [hide]

History

The beginning of bell creation and use dates back to 132 A.D. in China.The idea came from a Chinese philosopher by the name of Chang Heng, who invented the first known earthquake detector. He then connected a ringing device to the arm that moved during earthquakes so that a ring would be sounded during large seismic activity.

From China, the technology spread to the West, where it was used in church towers across Europe and the Western world.

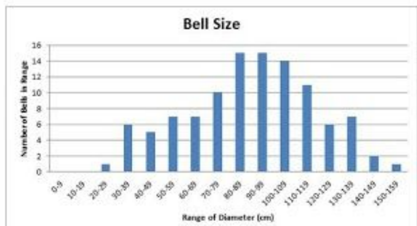
For more information about bell history, see our External Links.

Statistics

Venice has 229 documented bells which have been visited by Venice Project Center groups. The collected data helps illuminate many aspects of the bells, such as their conditions, commonalities, age, number, and size. By examining the conditional ratings of bells for trends, it is possible to determine the urgency for renovation across the city. It can also be determined if these trends have any correlation to the bell's founder or date of casting.

Bell Sizes

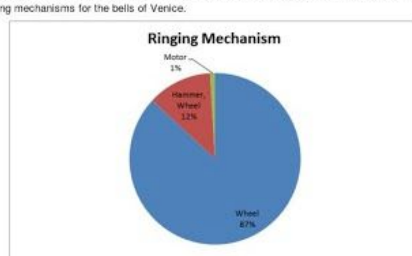
The largest bell documented from Venice is Bell #2 of Sant' Elena, which has a diameter of 152 cm, and the smallest bell documented is Bell #4 of San Nicolò dei Mendicoli with a diameter of 21 cm.



From the graph above, it can be determined that the most frequent bell diameter ranges from 80 to 99 cm. Ironically, the shape of the graph is approximately a bell curve. The average ratio of diameter to internal bell height is 1.22 with a standard deviation of 0.106. Therefore, the size of the bells may vary, but the shape is similar for all bells in the city.

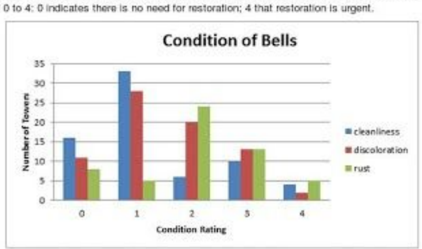
Ringing Methods

Most bells in the city employ the same type of ringing method. The use of a wheel or a hammer are the two most common forms of ringing. However, ringing with a wheel is most often used, as 87% of the bells in Venice are rung by wheel. The second most common form are bells rung by both wheel and hammer, with 12% of bells employing this method. The graph below illustrates the share of these ringing mechanisms for the bells of Venice.



Bell Condition

Because bells are an integral part of the material culture of Venice, it is important to track the their condition so it is possible to determine when and to what extent renovation is needed. As discussed in the Bell article, the materials that bells are made from, although durable, are still vulnerable to chipping, cracking, discoloration, corrosion, and rust. These condition criteria have been rated on a scale of 0 to 4: 0 indicates there is no need for restoration; 4 that restoration is urgent.



The majority of the bells measured have a conditional rating of 1 for both cleanliness and discoloration. This means that there is some discoloration and dirtiness but not a problematic amount. Rust had a slightly higher rating of 2, though this is still relatively minor. The bells that need restoration should have a rating of 4 for each category. Fortunately, there are 5 or fewer bells for each of the categories with ratings of 4. There seems to be little correlation between the three categories. While there seems to be a great number of bells with a certain rating for one category, there may only be a few rated the same in a different category. Perhaps, when considering a bell for restoration, only one type of deterioration must be remedied. However, from the data there are some bells with a rating of 4 in all categories, such as those in the bell tower of San Silvestro.

See Also

- Bell
- Bell Ringing
- Bell Tower
- Bell Towers

Bell

This page is a description of a typical Venetian bell. For an overview of all the bells in Venice, see Bells.

A Venetian bell, known in Italian as *campana*, has had many different uses. Before modern times, bells had more purpose than pure musical entertainment. They were signals of danger, disaster, and alarm. Many bells of today were built in medieval times, and were manufactured using a specific set of techniques and materials.

Contents [hide]

Bell Construction

The casting of bells is a delicate and precise process. The style of a particular bell depends upon the foundry in which it was made, along with the materials that compose it and the period of its creation.

Material of Bells

The most common material for bells is bronze, an alloy of copper and tin. Very rarely bells were cast in steel and cast iron. This shift in bell materials occurred mainly during times of war, when alloys such as bronze were in short supply since copper was needed in the manufacturing of some weapons. Around 1857 A.D. a combination of iron and carbon, also known as steel, became a material for bell-making. Not soon after it had begun being used it was discarded since the compound was deemed unsuitable for a material of bells.

Bell Casting and Founding

Bells have typically been made using the same process for over six centuries. A popular method of bell casting is to use sand-casting. In medieval times, when many bells were being produced, molds were made from clay to make a template for the bells. A bell mold had a center mold and an outer mold, where molten bronze was poured between the two and then allowed to cool to take the shape of a bell. Back in the middle ages, sometimes wooden templates were also used. Through the use of these templates the distinctive shape of the bells was formed.
For more information about bell founding, see external_LINK.

Acoustics of Bells

Bells like any other sound generating device can be broken down to a science. The frequency of the waves and thus the sound generated by the vibration is directly proportional to the diameter of the bell and the thickness of the metal. Bells are made to exact formulas so when a diameter is chosen, it is possible to calculate every remaining dimension of the bell and its musical note or tone. The frequency of a bell's note varies with the square of its thickness, and inversely with its diameter.

If the bell is mounted as cast, it is called a maiden bell. Tuned bells are worked after casting to produce a precise note. The bell's strongest overtones are tuned to be at octave intervals below the nominal note, but other notes also need to be brought into their proper relationship. Bells are usually tuned via tuning forks or by more modern electronic tuners.

Striking Methods

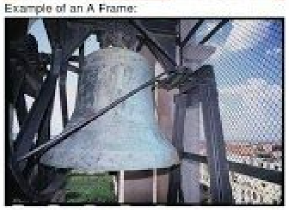
Another key factor in the ringing of the bell is how they are struck. The first method often portrayed in movies is the swinging method. Usually a rope is tugged from the ground that causes the entire bell structure to swing back and forth, and inside the bell, a clapper strikes the sides causing vibrations as seen below. This method is not advisable as it causes a great deal of bell movement, and over time this motion can damage the support structure and leave a streak mark formed by the clapper if the bell is not balanced. The other method is striking the shell of the bell. This causes less structural damage, but over time can leave dents which might ultimately deform the bell and alter its sound. The last common method, similar to the hammer method, is to swing the clapper while the bell remains stationary.

Bell Frame Design

Two bell frame types are primarily used to suspend bells, the H frame and the A frame. The H frame occurs when the bell is suspended on a cross bar made of heavy H castings usually composed of a durable metal material such as cast iron. Alternatively, H-frames can be stand-alone parallel legs with a single cross beam that holds the bell. A-frames are metal structures that form the shape of an "A" and attach the bell to the ground of the belfry as seen below The metal material resists twisting and provides a secure base for the bell. The popularity of this type of design resides in its greater convenience and construction. The last method of attaching a bell is to mount it to a circular support structure that is free to rotate. The structure is then rocked back and forth while the bell is held firmly on the wheel.

Example of an H Frame:

Example of an A Frame:



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Anatomy and Tuning of a Bell

The basic anatomy of a bell is fairly universal. On the top of the bell there is typically a wooden crossbeam called a yoke that the bell is attached to. The connecting piece is known as the crown. Commonly made of metal, the crown can be directly attached to the yoke, or the bell can dangle with the crown being tied to a series of leather straps. Connected to the crown of the bell is the head and shoulder section of the bell. This section is tuned to resonate one octave higher than the hum, or main note. The main section of the bell is referred to as the waist. This is the largest section of the bell and is tuned to resonate at a fifth, or quint, of the hum tone. The bottom section of the bell where the flare begins is known as the sound bow. This section is attached to the lip, the very bottom of the bell, and is responsible for the generation of the hum tone. The open bottom of the bell is the mouth. Within the mouth of the bell can be seen the clapper, which is usually a metal rod attached to a metal ball. The clapper hangs free from the shell of the bell so as to invoke independent movements. *For more information on bell ringing, see* ***Bell***

Bell Decoration

When ancient bells were cast, the moldings and decor on them were treated as a form of art. The inscriptions, figures, and design on each bell were well thought out by the founder and were intended to be a reflection of the founders work.

Most European bells are similar in their decorations, which usually include an inscription about where or when they were made or an engraving of a religious figure. Another trend founders have implemented was to design a trademark with a symbol or initials instead of writing out the full name of the founder.

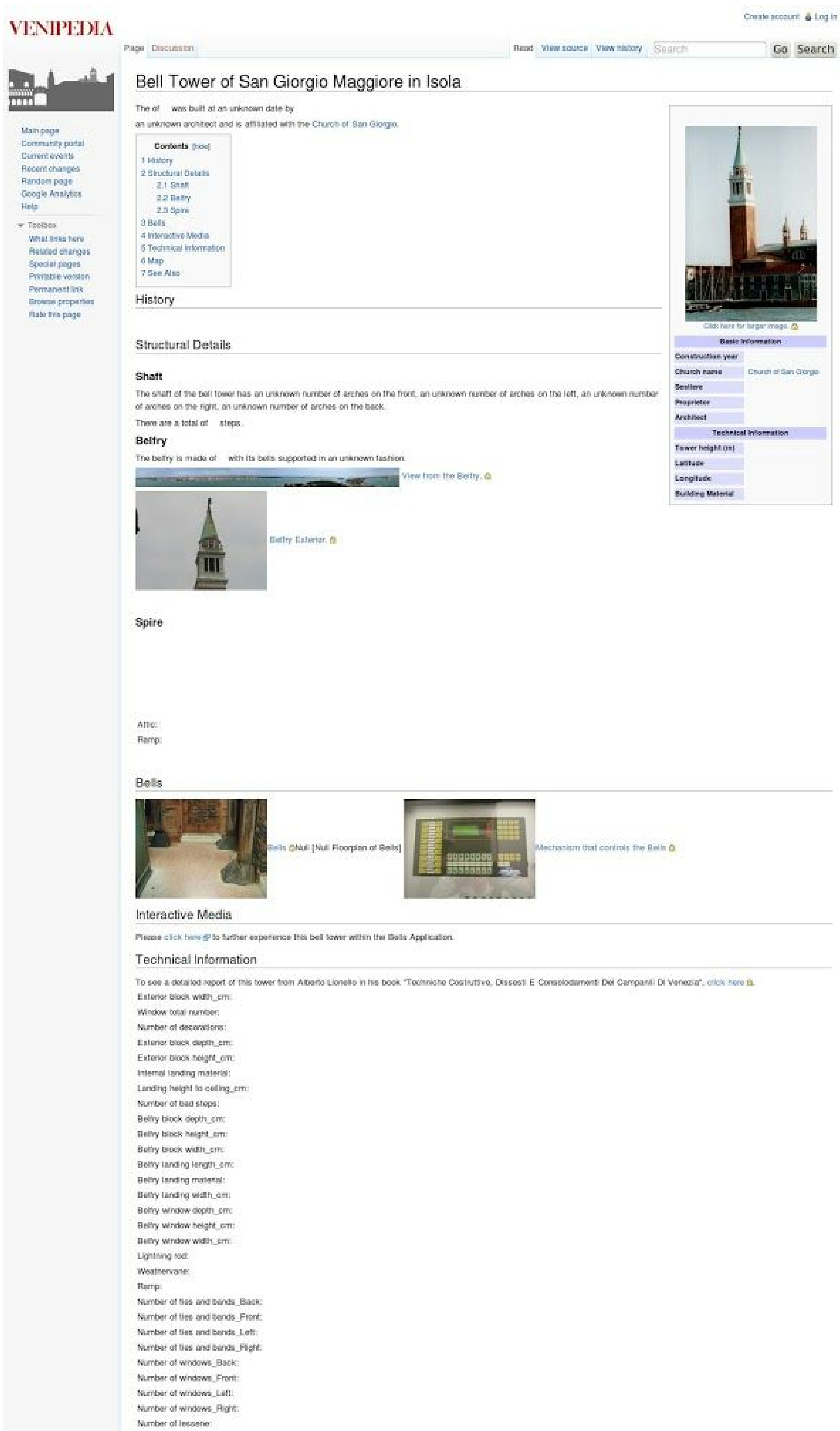
Historical figures are a common form of art found on bells. These include effigies of saints, angels, or royal leaders. In addition, one may find the shield of the patron who invested in the tower or church. However, the most frequently used decor were inscriptions which offer information of whom the bell was dedicated to, who the maker or donor was, when it was cast, and other supplemental information. These are typically in Latin, although some may be in the native Italian.

IMAGES with examples

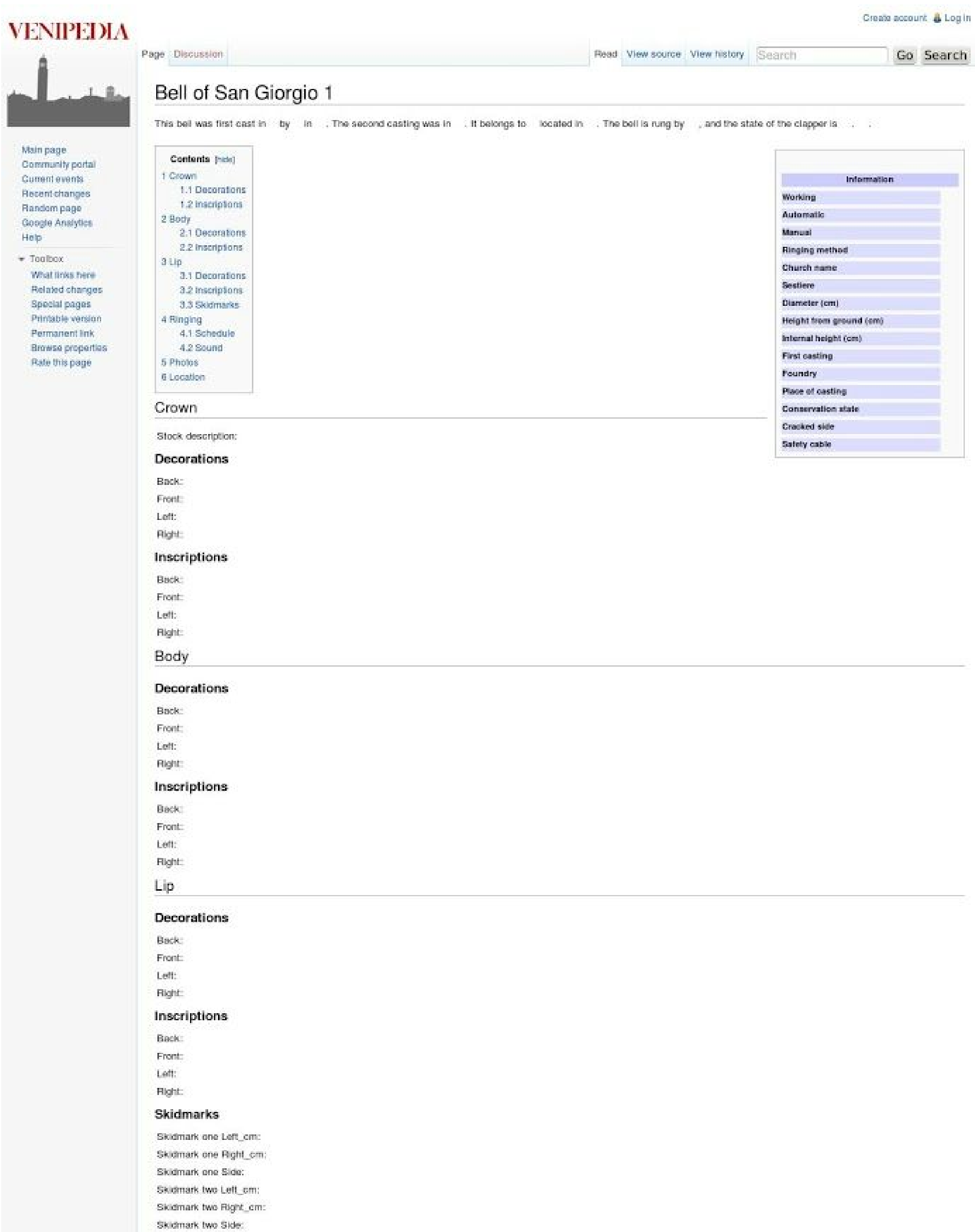
Bronze Corrosion

Most of the bells in Venice, being made of bronze, suffer from a cyclic degrading process known as Bronze disease. The disease refers to a chemical process in which the copper in bronze reacts with elements and moisture in the atmosphere creating a film signifying corrosion. Bell towers provide perfect conditions for bronze disease to propagate by leaving bells exposed to environmental conditions such as humidity, high winds, rain, and moisture. The thick green coating has the ability to transform the object by corroding the surface and possibly removing valuable artwork from its face. Many of the bells have intricate images exuding from their surfaces making corrosion a significant problem.
For more information on bronze corrosion, see external_LINK.

K. Venipedia Bell Tower Example



L. Venipedia Bell Example



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Toolbox
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Bell of San Giorgio 1

This bell was first cast in by in . The second casting was in . It belongs to located in . The bell is rung by , and the state of the clapper is . .

Contents [hide]

Information
Working
Automatic
Manual
Ringing method
Church name
Sestiere
Diameter (cm)
Height from ground (cm)
Internal height (cm)
First casting
Foundry
Place of casting
Conservation state
Cracked side
Safety cable

Crown

Stock description:

Decorations

Back:
Front:
Left:
Right:

Inscriptions

Back:
Front:
Left:
Right:

Body

Decorations

Back:
Front:
Left:
Right:

Inscriptions

Back:
Front:
Left:
Right:

Lip

Decorations

Back:
Front:
Left:
Right:

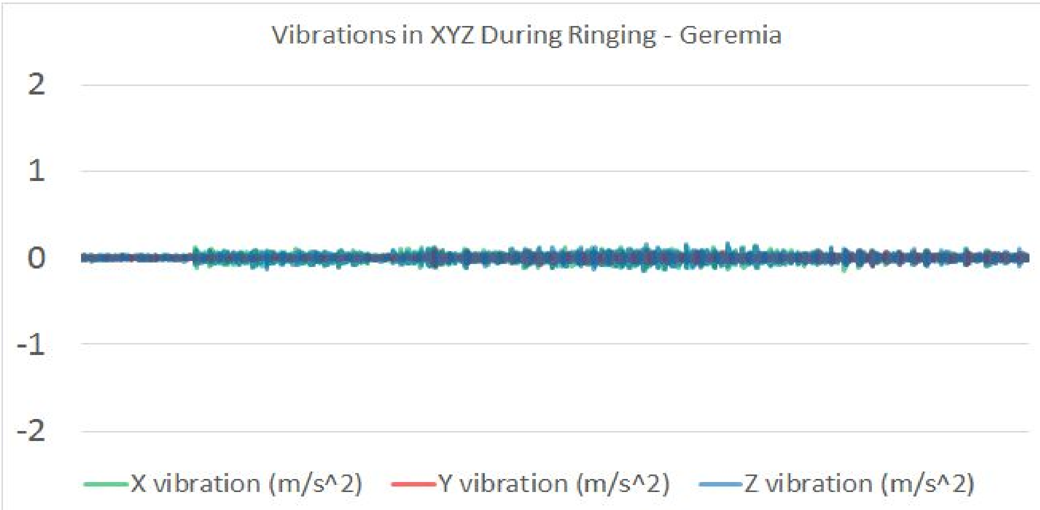
Inscriptions

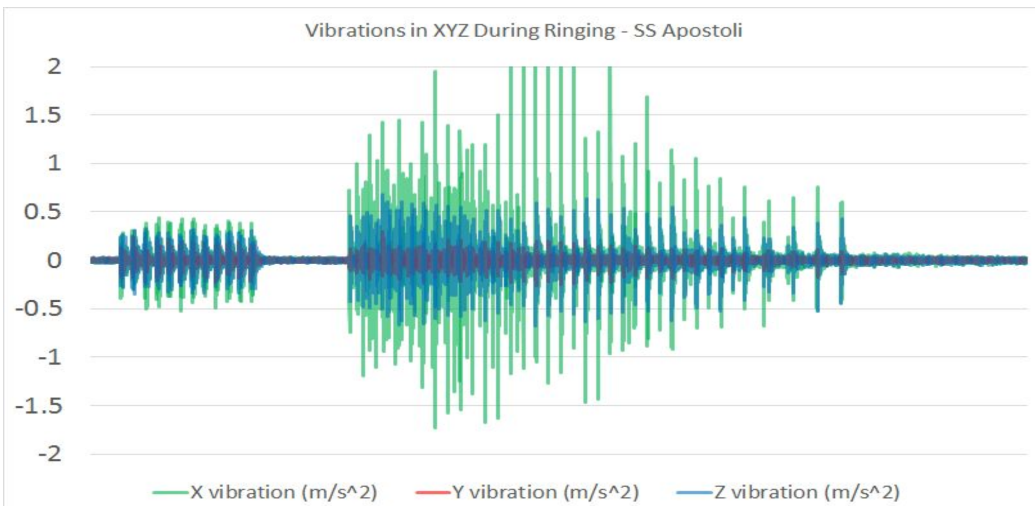
Back:
Front:
Left:
Right:

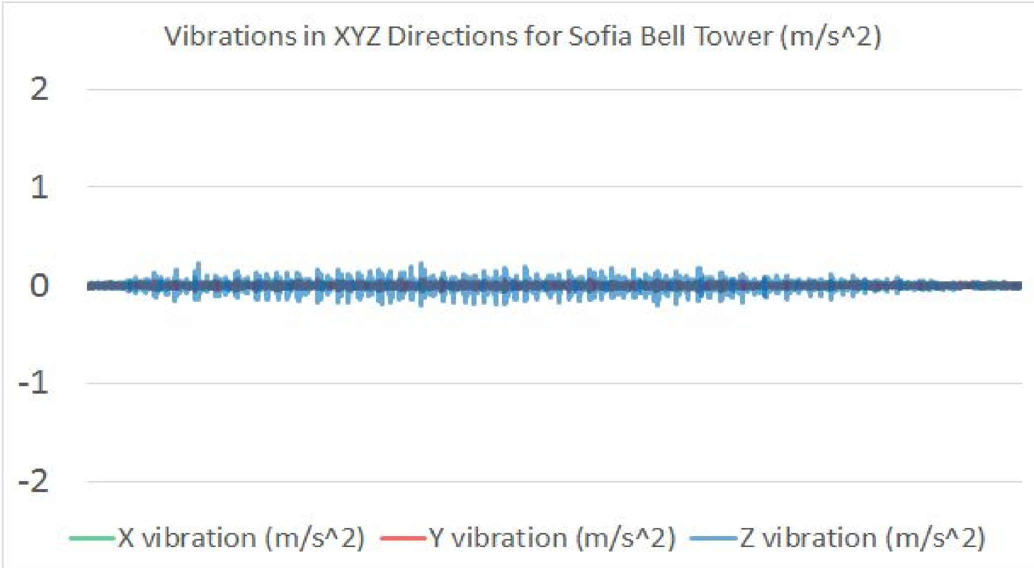
Skidmarks

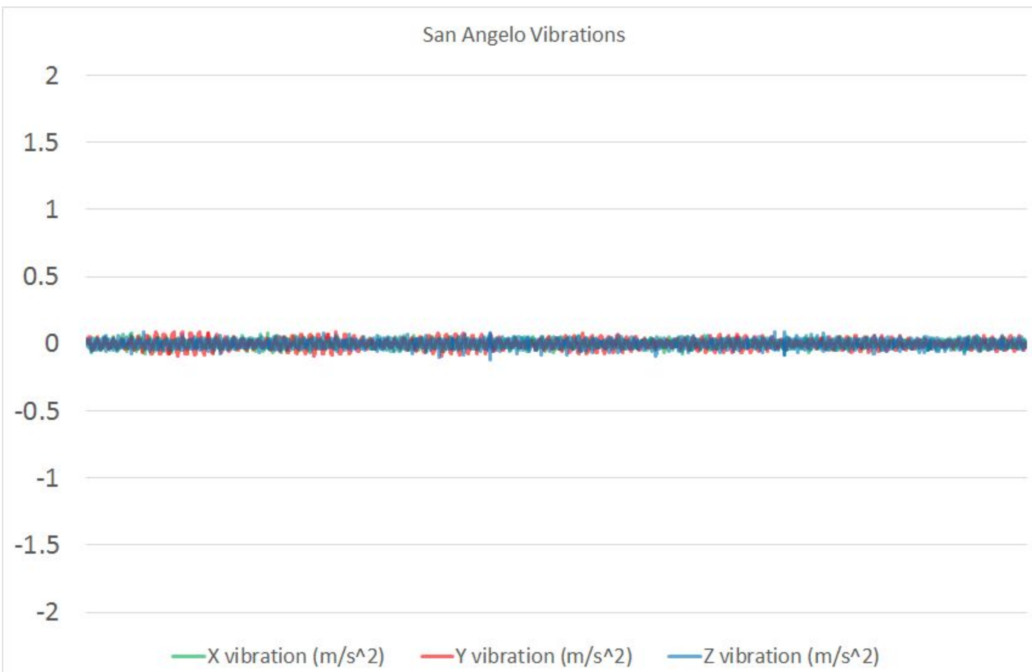
Skidmark one Left_cm:
Skidmark one Right_cm:
Skidmark one Side:
Skidmark two Left_cm:
Skidmark two Right_cm:
Skidmark two Side:

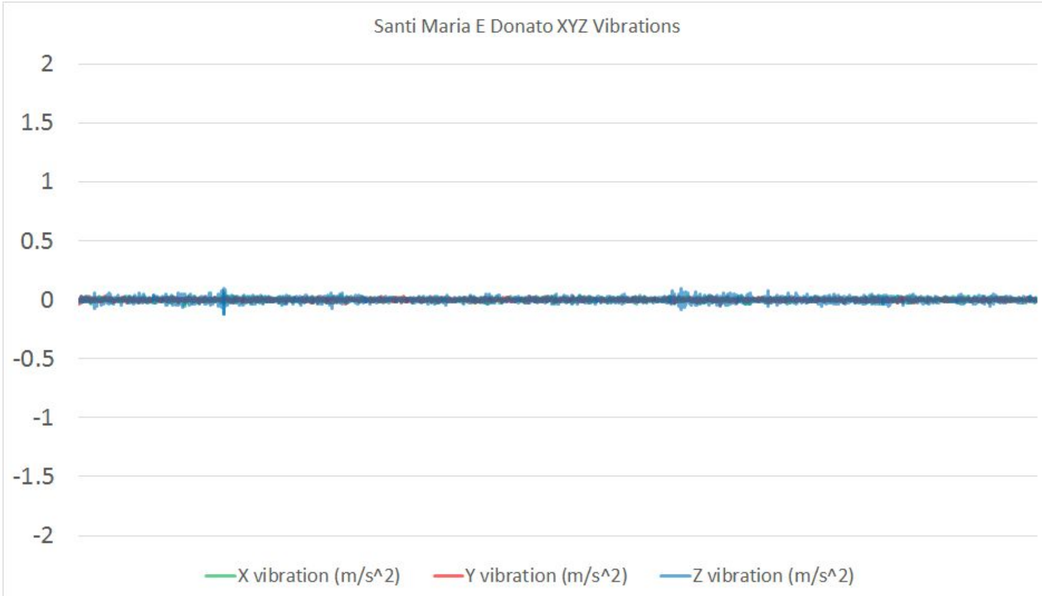
M. Collected Vibration Data






Vibrations in XYZ Directions for Sofia Bell Tower (m/s^2)
2
1
0
-1
-2
X vibration (m/s^2)
Y vibration (m/s^2)
Z vibration (m/s^2)


San Angelo Vibrations
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
X vibration (m/s^2)
Y vibration (m/s^2)
Z vibration (m/s^2)


Santi Maria E Donato XYZ Vibrations
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
X vibration (m/s^2)
Y vibration (m/s^2)
Z vibration (m/s^2)