VENICE FROM ABOVE:

An Effort to Preserve Venice's Bell Towers

An Interactive Qualifying Project Report Submitted to the faculty of

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In partial fulfillment on the requirements for the Degree of Bachelor of Science

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Abstract

Our project aids in the preservation of Venetian bells and towers by improving upon the Venice Project Center's database, achieved through detailed quantitative surveys of bell towers and creation of interactive virtual tours. To provide a more comprehensive presentation of bell tower data, the Bells Web App was redesigned with improved functionality and visuals. The project explored new promotional methods to increase traffic to the Bells App to increase awareness of the state of the bells and towers. This project also investigated ways to measure the effects of bell swinging forces to determine their impact on the structural integrity of a tower. Finally, the project assessed the safety and accessibility of bell towers to determine if they can be opened to visitation in the future.

Executive Summary

The churches, bells, and bell towers of Venice, Italy have long stood as symbols of the city's rich cultural heritage; however, they have fallen into neglect in recent years, in part due to a lack of support for their upkeep. As towers degrade over time, they develop cracks and other structural issues and without repair and proper maintenance, they could collapse from earthquakes or other natural occurrences.

To assist in the preservation of these towers, the Venice Project Center (VPC) has been working to collect and record data on bells and towers around the city. Since 1992, teams working at the VPC have collected data on 58 of the 136 bell towers and 222 bells as of 2016. This data varies from tower to tower but generally includes photos, statistical information, and sound recordings of the bells. More recently, teams have explored ways to make 3D models of the bells or towers, allowing people to explore the insides of the churches and bell towers without physically visiting them. Our project builds upon the experience of the previous nine projects in order to organize not only existing and new information, but to also provide a solid foundation for future restoration and reutilization of Venice's bells and bell towers. In order to achieve our goals, we set out to expand the VPC catalogue of bells and bell towers; to propose a methodology to experimentally assess the safety and structural integrity of the bell towers; to explore the possibility of re-utilizing the bell towers for visitation; and to increase public awareness of the state of the bells and bell towers.

Our first goal was to provide a solid foundation for future restoration and reutilization of Venice's bells and bell towers by improving the VPC's collection and presentation of data. We achieved this by collecting new data on bells and bell towers to be added to the VPC's database and by presenting all the data collected since 1992 in an organized and interactive way through our significantly revised version of the Venice Bells Web App. Over the course of this project, we visited 11 bell towers in the sestieri of Dorsoduro, Giudecca, San Marco, Cannaregio, Santa Croce, and San Polo, shown on the map below in Figure I. During these 11 surveys, we documented 38 bells, the exteriors of 10 towers, and the interiors of 9 towers.

Figure I: Map of Venice with the towers that were studied in our project

After collecting data on 10 towers, we defined scoring metrics to give the towers quantitative condition ratings based on the data we collected on their interiors, exteriors, and bells. We assigned weights to differentiate the fields that we found most important and calculated overall conditions ratings for each bell tower. We found that 9 towers that we had sufficient data to rank were in very good condition as a whole compared to last projects, with only Sant'Eufemia receiving a score of below average. The relative rankings can be seen below in Figure II, with yellow representing an average score, green above average, and orange below average.

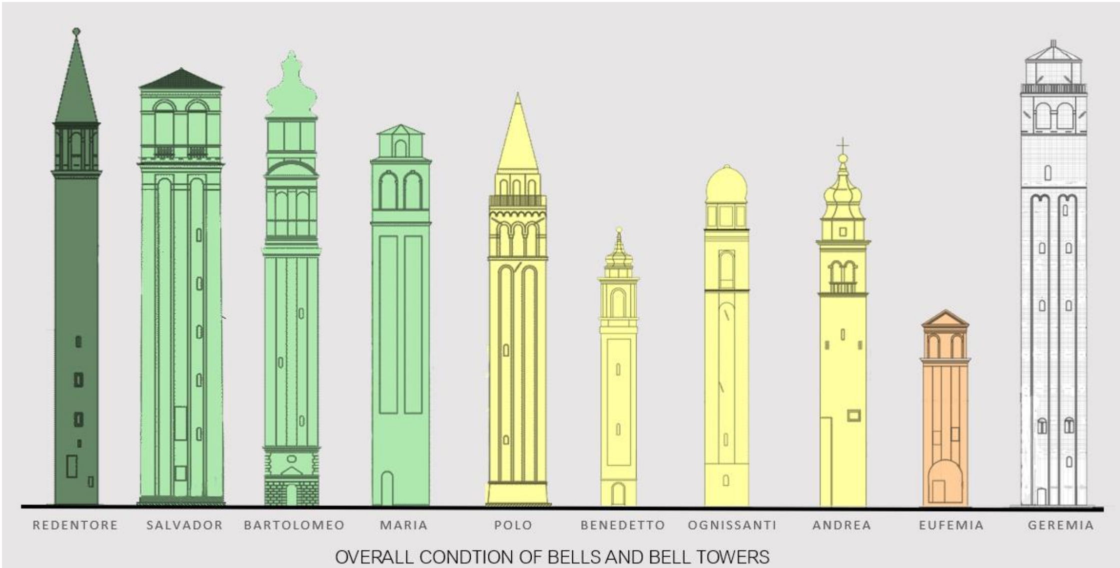

Figure II: Rankings of Towers by Overall Condition

Additionally, we developed improvements to the VPC's presentation of the data that has been collected by updating the Venice Bells Web App. The biggest and most impactful change we made to the Bells App was the transition to a new framework that excels at rendering fast and clean front-end clients. As a result, the new version of the website can provide a cleaner aesthetic quality, quicker than the previous version. Furthermore, the transition to the new framework improves the scalability of the website for the future. It is significantly easier to learn than the old framework, which makes it easier for future VPC projects to expand on our work, especially if they have little prior experience programming. Additional novel features of the Bells App include a new homepage, an updated map view, updated tower icons and popups, a new list view, a new layout for the tower info page and overall greatly improved aesthetics of the website. Finally, we used a 360° camera in the interior and exterior of the towers to document them in depth and to allow exploration of the tower through an online 360 Virtual Tour. The new pages can be seen below in Figures III and IV.

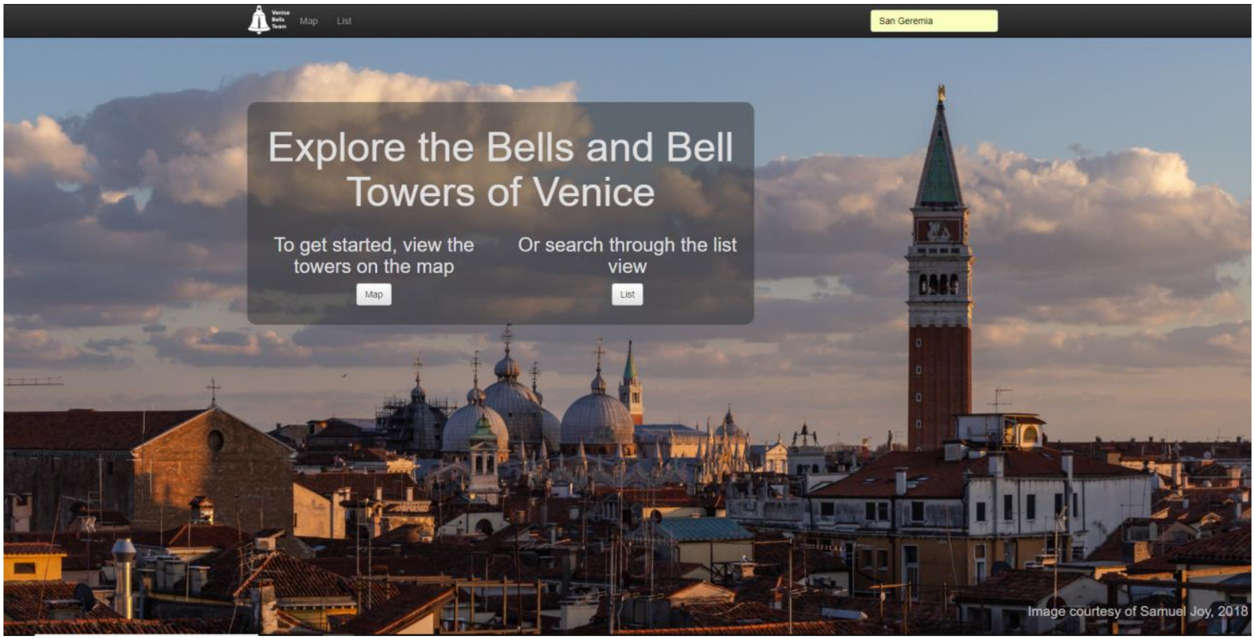

Figure III: Updated Home Page

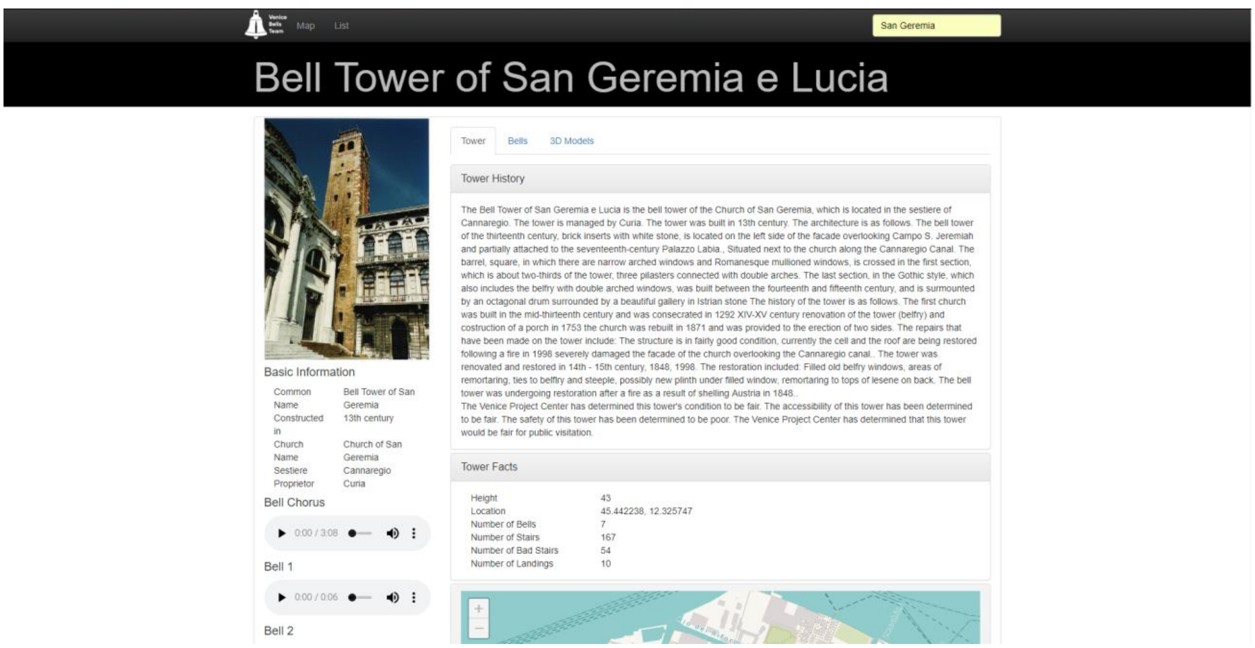

Figure IV: Updated Tower Page

We also explored the feasibility of a methodology to detect deficiencies in a bell tower based on analysis of motion in the tower caused by inertial forces created by bell swinging. We used AxisVM, a professional structural engineering software, to create an accurate geometric model of the bell tower of San Salvador in order to determine the natural frequencies of the structure. We then performed a case study on the tower of San Salvador by measuring accelerations in its belfry due to the forces created by the swinging of bells. By comparing the frequencies of tower motion to the natural frequencies, we hoped to be able to draw conclusions about the overall structural integrity of the bell tower of San Salvador. Our results were not sufficient to confidently draw conclusions about San Salvador due to several shortcomings; however, we were able to provide a procedure that could easily be adapted by future projects in order to achieve more meaningful results. Of particular note is our process for determining the natural frequencies of a bell tower, which are important in assessing their reaction to any stimulus, such as earthquakes or wind.

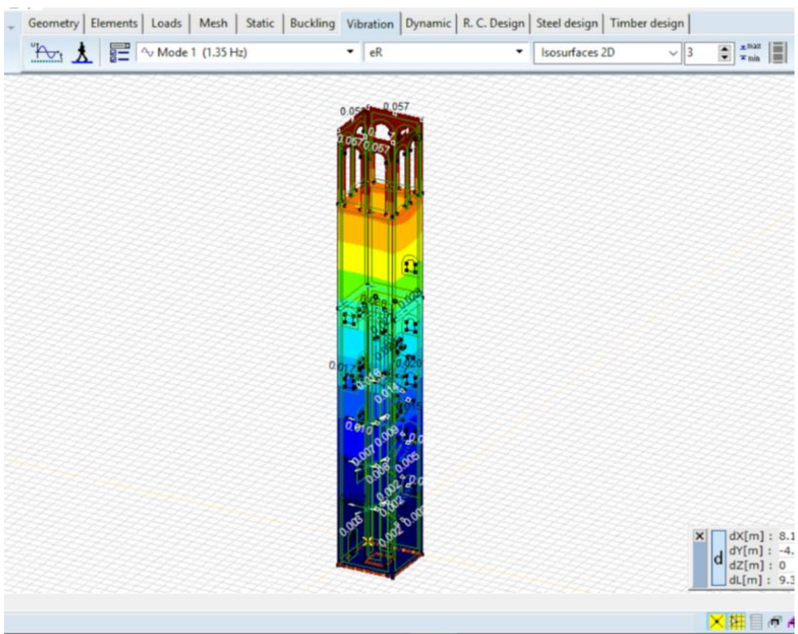

Figure V: Model of San Salvador after Vibration Analysis

We also evaluated the accessibility of bell towers to visitors and figured out ways to increase public awareness of the state of the bells and bell towers. Our data collection and photographs have gone towards the preservation of the tower in documentation. This allows for the tower to have a historic record and reference for the tower to be rebuilt. During the course of this project, we visited 11 bell towers in all six regions (sestieri) of Venice. We documented 38 bells, the exteriors of 10 towers, and the interiors of 9 towers. We compiled data from interior, exterior and bell analysis, and devised a scheme of assessment of visitability for all towers we studied.

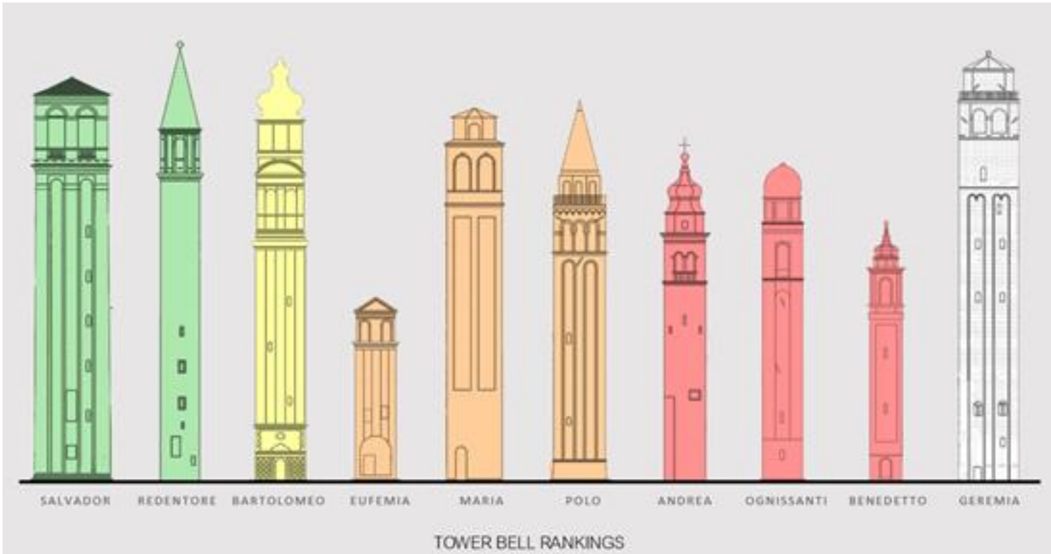

Figure VI: Tower Visitability Scoring

Figure VII: 3D printed model of San Geremia and picture of San Geremia bell tower

In conclusion, over the course of 7 weeks we have contributed significantly to the efforts of the VPC, SerenDPT and the Curia Patriarcale to document, improve the presentation of Venice's bells and promote the preservation of cultural heritage in the city of Venice. We have also developed and implemented a simple but accurate model to assess safety issues that may be caused by bell swinging. Furthermore, we developed methods to alert people to the state of Venice's bells and bell towers, as well as expanded on the VPC's interactive presentation of the data it has collected since the first bells and bell towers project in 1992.

Finally, we have compiled a list of recommendations for future WPI VPC bell-related projects that focus on three areas. Firstly, on data collection, storage and accessibility, we propose the reorganization and standardization of the database hoping our templates will be the stepping-stone for a future project. We also propose specific additions to the Web App which we had no time to achieve, such as the possibility of allowing users to get directions to a specific bell tower from anywhere in Venice and the possibility to donate towards the restoration of a bell tower. We also propose that a future project works with the Curia Patriarcale to establish a business model towards restoration. Secondly, on the assessment of structural integrity of bell towers, we would propose that future projects expand our case study for additional bell towers and/or wish to incorporate new technologies that may provide greater precision and broader functionality. An example for a potentially fruitful project would be to install devices in bell towers that can accurately monitor vibration data within a long-term framework in order to detect cases in which bell swinging is detrimental to tower health and stability. Thirdly, on the visitability of bell towers, we have made specific recommendations based on the exteriors, interiors and bells of the towers we have documented. We sincerely hope that future projects will build upon our work on all three of these directions so that these rich cultural monuments become again a main aspect of Venetian life and heritage.

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Authorship

All members contributed equally in the writing of this paper.

Acknowledgements

This project would not have been possible without the extensive help of many collaborators, and as such we would like to recognize those who have contributed to its success.

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At the Venice Project Center, we extend our gratitude to Piero Toffolo, Michele Vianello, Sarah Puccio, Andrea Toffanello, and Nicola Musolino. We are eternally grateful to Piero and Michele for their commitment to helping us along the way. They accompanied us to every bell tower we visited to ensure that every visit went smoothly, including assisting with data collection, warning us of dangerous conditions, and translating for us. Sarah was also an essential part of the tower visit process, as she coordinated with the pastors to schedule visits for us; without her, we would not have been able to visit as many towers as we did. We are also thankful to Andrea and Nicola for their help in the design of our interactive media. Andrea helped immensely with visual design no matter what we needed it for, and Nicola guided us in the recreation of the Bells App and integration with the VPC's database.

Next, we extend our thanks to all who have advised us in our structural integrity experiments: Margherita Ganz and Professor Mirabella Roberti of Politecnico di Milano, Theodoros Kantzos, Professor Androniki Miltiadou-Fezans of the National Technical University of Athens, Francesco Trovò, and Professor Leonard Albano of WPI. We are extremely thankful toward Margherita and Prof. Roberti, as they actively collaborated with us on our structural study, and without their support we would not have achieved the same level of success. We also give a special thanks to Margherita for providing us the graphics of bell towers used throughout our report. Additionally, we want to thank Theodoros Kantzos and Prof. Miltiadou-Fezans for their consistent feedback throughout the project that helped us develop a sound methodology. We are grateful to Francesco Trovò for kindly sharing detailed geometric diagrams of many bell towers of Venice in order to assist us in building our model of San Salvador. We are also grateful to Prof. Albano for his guidance in our research as we began to develop our methodology during PQP.

Finally, we would like to thank the past bells and bell towers teams of the Venice Project Center for providing a solid foundation on which to base our work. Our project is a continuation of 26 years of bell and bell tower documentation, and we realize that our work is most impactful only when placed in the context of the entirety of the VPC’s bell tower studies. In particular, we are grateful to the 2016 bells team of Rachel Huntley, Frederick Metters, Obatola Seward-Evans, and Frederick Brokaw for their help, especially Rachel for actively communicating with us throughout the project.

1. Introduction

Throughout history, religion has been a staple of daily life, especially in Italy, a country known for its religious piety. Italy is a predominantly Catholic country, and the church has been an integral part of Italian culture ("Global Religious Futures," 2016). Nearly as common as the churches themselves are bell towers, whose bells have historically been used to signal time and call the people to worship (Rombouts, 2014). The majority of bell towers are centuries old, which means they have been subject to several causes of damage for many years (Cotton, 2016). These damaging factors include vibrations from the ringing of bells, forces on the tower due to swinging the bells, and erosion due to long term exposure to weather (Fitzner & Heinrichs, 2001). As bells and bell towers are exposed to these forces they deteriorate, detracting from the city's cultural heritage. In extreme cases the towers could even collapse, as did the Civic tower of Pavia, Italy in 1989 (Montalbano, 1989). Routine maintenance on bells and bell towers is an important part of controlling their deterioration.

The churches, bells, and bell towers of Venice, Italy have long stood as symbols of the city's rich cultural heritage; however, they have fallen into neglect in recent years due to a lack of support for their upkeep. Between 1971 and 2011, Venice has experienced a 45% decline in residential population, with many of the residents being replaced by tourists (Comune di Venezia, 2012). The population decline, combined with a nationwide drop in church attendance from 18,366 to 15,752 between 2006 and 2016, has caused an overall decline in the number of parishioners in the city (Istat, 2018). Because there are no longer enough people to justify holding mass, many churches have either begun cancelling masses or even closing down entirely (Squires, 2017). Closures are problematic for parishes because offertory donations during mass are the primary source of funding in the Catholic Church ("Church Finances," 2014). Churches on average spend 18% of their budget on facility upkeep, including maintenance on their bell towers (Mika, 2018). Without proper funding, individual parishes cannot properly protect their bell towers against the many causes of damage, and the towers fall into disrepair. A 2015 project by the Venice Project Center (VPC) collected data on 21 bell towers in Venice; according to their methods, 41% of those towers were in either poor or very poor condition (Bove, Gallagher, Hickey & Honicker, 2015). As structures of cultural and religious significance, it is important that the bell towers be properly documented so they can be properly preserved.

To assist in the preservation of these towers, the VPC has been working to collect and record data on bells and towers around the city. Since 1992, the teams working at the VPC have collected data on 58 of Venice's 136 bell towers as of 2016 (Bove et al., 2015; Huntley, Metter, Steward-Evans & Browka, 2016). This data varies from tower to tower but consists of some combination of photos, statistical information, and sound recordings of the bells. More recently, teams have explored ways to make 3D models of the bells or towers, allowing people to explore the interiors of the churches and bell towers without physically visiting them.

Though extensive research has been completed on the bells and towers, a significant portion of bell towers in the city remain undocumented. Before our contributions, 43% of bell towers have been extensively documented and had their data stored in the VPC's database. Furthermore, there are some inconsistencies in the database because the data has been completed by several teams over many years using slightly different methodologies. Finally, the VPC's presentation of all its data is just as important as its collection because the bells and bell towers are iconic parts of Venice's culture that should be appreciated by residents and visitors alike. While the current version of the VPC app is more than satisfactory, new features could be added to make it an even more complete experience. Additionally, optimization for mobile devices will help to increase the audience for the VPC's data and interactive media due to the increasing popularity of mobile browsing.

The goal of our project was to provide a solid foundation for future restoration and reutilization of Venice's bells and bell towers by improving the VPC's collection and presentation of data. We simultaneously developed a more interactive and more easily accessible web application for immersive experiences with Venice's bell towers. In order to accomplish this goal, we addressed four specific objectives. The first objective was to expand the VPC's catalogue of bells and bell towers. Our second objective was to develop a methodology to assess the safety and structural integrity of bell towers. The third objective was to explore the possibility of re-utilizing the bell towers for visitation. The final objective was to increase public awareness of the state of Venice's bells and bell towers. These objectives added information to Venipedia and the Venice Bells Web App, made that information more accessible to the public, and created a foundation for future projects to work on restoring the bells and bell towers.

2. Background

Bells were introduced into churches around the year 605 A.D. and were widely used to call parishioners to worship. Venice was no exception, with 136 bell towers scattered throughout the lagoon and 87 in the city (“Bell Towers”, Venipedia). While the bells are not used nearly as much as they used to be due to declining church attendance and deterioration, they remain an integral part of the city’s culture and identity, and they must be documented and physically maintained in order to preserve this part of Venice’s heritage.

In order to properly document and preserve the towers and bells, it is important to understand why they are important to the city. To do this we will first explore the importance of the Catholic Church in Venice, along with the role of bells in the Church. We will also explain the decline of religious participation and how it indirectly affects bells and bell towers. This will be followed by a section describing the use, anatomy, and decoration of the bells. We will also detail the architectural styles, anatomy, and maintenance techniques of the bell towers. All of this information will be crucial in determining what data should be collected in order to most effectively document the bells and towers.

2.1 Religion in Venice

Since its founding in the 5th century, Venice has always had a strong affiliation with the Catholic Church. In 1451, the Patriarchate of Grado was merged with the diocese of Castello to form the Patriarchate of Venice. From there, it grew to become the ecclesiastical province of Venice (“History of the Patriarchate,” n.d.; Bove et al., 2015). Almost all of the churches of Venice are Roman Catholic, with Greek Orthodox, Armenian Catholic, Evangelical Lutheran, and Methodist comprising the rest (Cotton, 2016). The demographics of the people match those of the churches, with 85.1% of the population living within the Archdiocese of Venice identifying themselves as Catholic (Cheney, 2018).

2.1.1 Organization of the Catholic Church

The Catholic churches in Venice fall under the authority of the Archdiocese of Venice, which acts as the head diocese of the Ecclesiastical Province of Venice. In addition to the Archdiocese of Venice, the province contains the smaller dioceses of Adria-Rovigo, Belluno-Feltre, Chioggia, Concordia-Pordenone, Padova, Treviso, Verona, Vicenza, and Vittorio Veneto. With all of these diocese contained within the Ecclesiastical Province of Venice, the province is actually much larger than just the archdiocese itself. As shown in Figure 2.1, the province (shown in light blue in northeastern Italy) occupies much of the territory surrounding the mainland City of Venice.

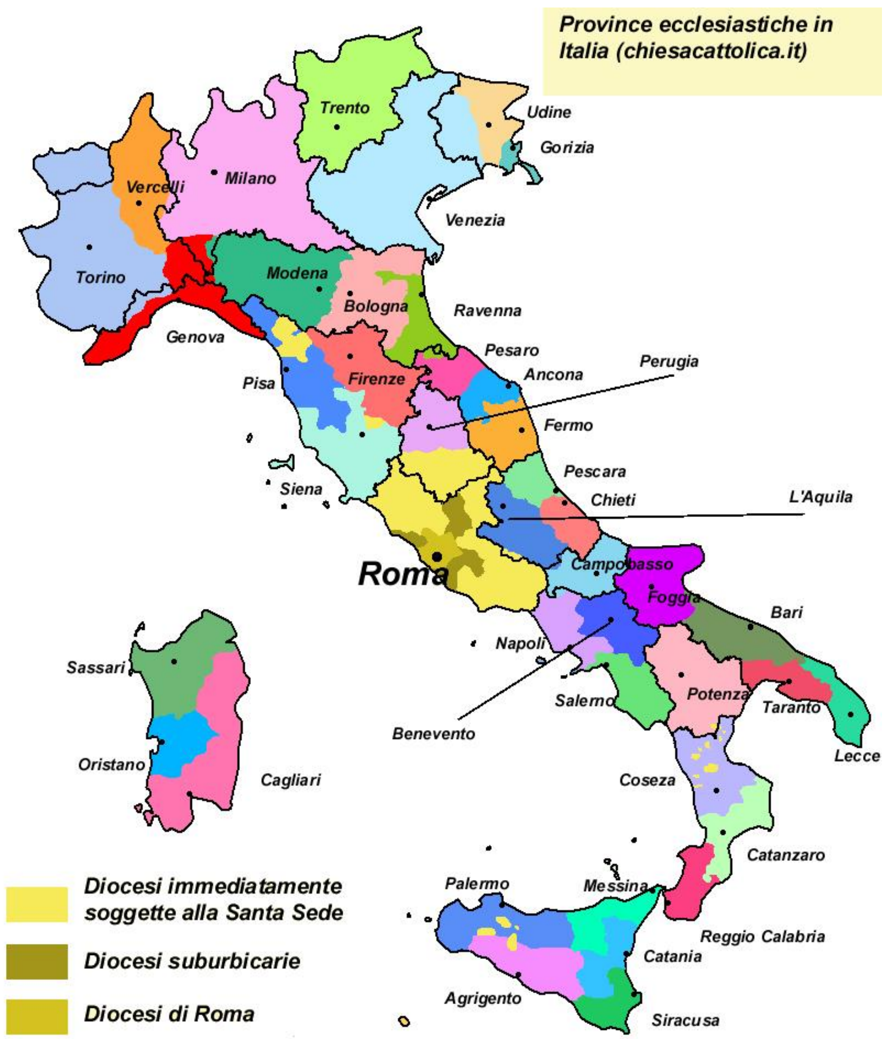


Figure 2.1: Dioceses of Italy (Wento, 2007)

The Archdiocese of Venice is headed by a bishop, currently Francesco Moraglia, appointed by the Pope, whose role is to run both the archdiocese and the ecclesiastical province as a whole. Within the Archdiocese of Venice is the Curia Patriarcale, an administrative body that assists the bishop by directing pastoral activity. The Curia is made of up several ordinaries, who act as board members in charge of particular areas of interest. Of particular note to our project is Don Gianmatteo Caputo, Director of Pastoral Tourism and Cultural Heritage, whose role is to oversee all matters related to visiting and preserving churches throughout the province. (History of the Patriarchate, 2018).

2.1.2 Role of Bells in Churches

Church bells have played a fundamental role in the history of countries, communities and places of worship throughout the world. In addition to calling people to prayer, bells have historically been used by churches as timekeepers, announcements for community gatherings and means of communication to warn civilians about natural catastrophes or invader attacks during war. In the words of Henry Wadsworth Longfellow, "Bells are the voice of the church" ("Church Bells", 2018), as churches have used bell ringing to influence and summon their parishes.

However, the use of bells has declined in modern day Venice. A decree was issued by the Roman Catholic Church in 2012 which ordered the city's churches to ring their bells in "moderation," as a result of chronic complaints from Venetians, suggesting that the constant bell ringing was a nuisance in their everyday lives. The resolution represented a settlement between freedom of religion and the city's increasingly secular population (Squires, 2012).

2.1.3 Decline in Church Attendance

Despite its rich religious history, Venice's religious interest has experienced a gradual decline in recent years. A study conducted by the Patriarchate of Venice concluded that only 15 percent of worshippers go to Mass every Sunday (Vezzoni & Bialcati-Rinaldi, 2010). This same study also showed that a mere eight percent had been to church at some point in the last month and in total, only 23 percent were shown to actually go to church regularly (Moore, 2007). In a similar trend, weekly church attendance dropped from around 175,000 after World War II to just 55,000 in 2017 (Squires, 2017). Due to the decrease in attendance, the number of churches in

Venice is far greater than the demand requires, and many churches have shut down as a result (Squires, 2017). With so many churches being shut down, many of the bells and bell towers are also being abandoned and left to fall into disrepair.

2.2 Relevant Information for the Documentation of Bells

In order to effectively document bells, it is important to understand their physical characteristics and function. These bells were cast centuries ago and have a great deal of history and craftsmanship tied to them. Every portion of the bell produces its sound by the vibration of its anatomical curves when it is struck. Even the bells' inscriptions are important to record as they stand witness to the history of its founder and purpose. Understanding the bells' structure and design is necessary for preservation or even casting replicas of bells should the originals become unusable.

2.2.1 Anatomy of a Bell

There are two basic shapes a bell design follows. First, there is the cup form, or open bell, which is the most common design. Open bells are used in many Western European bell towers, and are characterized by their flared sides. A shallow flare starts about two thirds of the way up the shell, growing more intense as it nears the bottom. The other form is the closed bell which has a loose pellet inside a hollow metal shell which rings against the shell when the bell is shaken. Sleigh bells are common examples of closed bells (Rech, 2014).

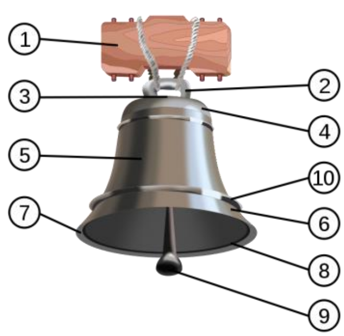


Figure 2.2: Parts of a Bell (Malyszkz, 2011)

1. yoke, 2. crown, 3. head, 4. shoulder, 5. waist,

6. sound ring, 7. lip, 8. mouth, 9. clapper, 10. bead line

The majority of church bells are cup bells, shown above in Figure 2.2. It is important to note that the profile of a bell is responsible for the modes of vibration. The vibration pattern is responsible for determining the frequencies and partials that can be heard, giving each bell a unique profile of tone intensities. Church bells are commonly hung from a wooden crossbeam called a yoke. The yoke can be directly attached to the crown of the bell, or the crown can be hung from ropes or belts connecting it to the yoke (Rech, 2014). The rest of the anatomy will generally define the sound the bell produces when struck. The top of the bell, known as the shoulder, resonates at one octave higher than the hum, the main note produced by the bell (Rech, 2014). Next, the waist of the bell, which is the large section in the middle of the bell, resonates at a fifth of the hum to produce a chord with the main tone. The main hum is produced by the rim surrounding the bottom of the shell, known as the lip. The lip is both the most flexible and heaviest part of the bell, making it the largest contributor to the bell's sound. As a result, the lip produces the main hum, and all the vibrations resonate out of the mouth of the bell. The bell is rung when the clapper strikes either the inside or outside of the bell, causing the various part of the bell to vibrate (Rech, 2014).

2.2.2 Bell Decoration

Similar to bell shape and design, the decoration of bells is also an important feature to study. While bell ornaments vary from inscriptions to other complex art designs, bell design is relatively similar throughout Western Europe (Tyack, 1898). The casting shape or ornate foliage around the border of bells identifies the bells' founders and reflects their artistic skill. As they do with these decorative borders, bell founders place unique initial crosses in the inscriptions of a bell to mark their work. The crosses are placed either at the beginning of an inscription or in between each character. Furthermore, bell founders typically position a stamp or trademark with their initials in the form of a circle or shield (Tyack, 1898). Bible verses, quotes, or the names of donors or church owners are commonly found on bell inscriptions as well. There are also sometimes inscriptions that indicated the order in which the bells should be rung (Tyack, 1898). Finally, bell founders would often include historic or religious figures to further decorate the bells, accompanied by depictions of angels or saints (Tyack, 1898). Most inscriptions were written in the founders' native language, which is typically Latin or Italian for Venetian bells (Tyack, 1898). The intricate inscriptions found on bells are an integral part of their cultural heritage, so it is imperative that they be documented before they are lost to wear.

2.2.3 Ringing a Bell

There are two main philosophies for bell ringing systems; one is implemented on Western bells whereas the other is used for Asian bells. Western bell philosophy is centered around the idea that the bells are actively struck by a piece of metal hanging in the center, called a clapper. This philosophy is mainly divided in three distinct swinging systems: English, Central European and Spanish (Ivorra & Pallares, 2006; "Bell Ringing," Venipedia). In the English system, which is also incorporated in Northern Italy, bells swing in a complete circle (360°), thereby changing the direction of the swing in each cycle. In the Central European system, which can be seen throughout Italy, bells swing around their axes on angles between 55° and 160°. Lastly, in the Spanish system, the bells are generally fixed directly to the tower's windows and always swing in the same direction. Furthermore, a large counterweight is provided, to make the bells more well balanced (Ivorra, Pallares, & Adam, 2011). On the other hand, Asian bells are struck by a wooden hand mallet or a swinging horizontal beam (The Editors of Encyclopaedia Britannica, 2014; "Bell Ringing," Venipedia).

The way in which bells are struck has a very significant impact on the resulting sound. For Western bells, there are two striker designs that are used to ring the bells. The first of which would be the use of a clapper. The clapper hangs from the top of the shell of a bell, and swings freely to ring the bell when it strikes the inside. One use of the clapper, as shown in Figure 2.3, would require the entire bell to be swung via pulleys and a rope to get the clapper to strike the inside of the bell. This swinging method is potentially dangerous, as the swinging of heavy bronze bells exerts force on the sides of the tower. Additionally, unbalanced swinging of the bell can cause dents or skid marks on the inside surface of the bell as the clapper strikes the surface unevenly (Heywood & Lewis, 1914). Another implementation of the clapper, shown in Figure 2.4, is to swing the clapper alone while keeping the bell itself stationary. While reducing the danger to the bell tower, this method increases the risk of damage to the bell via "clocking," a process in which the clapper becomes unbalanced and strikes the bell below the sound bow.

Clocking can cause dents or cracks to the bell (Heywood & Lewis, 1914). The final method of striking, shown in Figure 2.5, is the use of a hammer to hit the outside of the bell. Similar to the swinging clapper method, this method can wear down the shell more quickly than swinging the bell, this time causing dents and cracks to the outside of the bell (Rech, 2014). Despite their respective advantages and disadvantages, all of these methods wear down the bell if done improperly or for long periods of time, eventually causing the sound to deteriorate and the bell to crack.

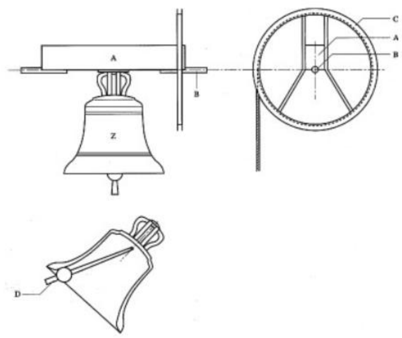


Figure 2.3: Method 1 Swinging the Bells (Schaferk80, 2015)

Figure 2.4: Method 2 Swinging the Clapper (Rech, 2014)

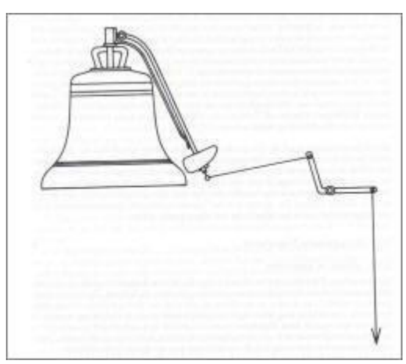


Figure 2.5: Method 3 External Hammer (Rech, 2014)

2.2.4 Bell Frames

There are two common ways to hang a bell in order to ring it: H-frames and A-frames. H-frames are found more commonly in bell towers than A-Frames (Heywood & Lewis, 1914). They are built with beams running across the tower above where the bell will hang, with one or more beams connected perpendicularly to these main beams, resembling a letter "H." The bell is hung from the central cross beam. A-frames are less common than H-frames, using the floor of the belfry as support rather than the walls. A-frames resemble several letter "A's" set in the floor of the belfry parallel to each other. A central beam runs between the supports to hold the bell (Heywood & Lewis, 1914; Dutton, 2017).

The implementation of the bell frames within the belfry is a critical point in the design of a structurally sound bell tower. As the bells swing, they exert force on the supporting frame, which is transferred to the walls of the tower itself. The most important characteristics of a bell mounting with regard to structural stability of the tower are flexibility in the bell frames and elasticity in the supports that secure the frame to the tower and flexibility (Dutton, 2017). In order to lessen the force felt by the walls of the tower, the bell castings should be secured to the wall as rigidly as possible via angle plates. Furthermore, the bell frame itself should be rigid so as to prevent the accumulation of additional forces that an elastic frame would generate as the bell swings (Heywood & Lewis, 1914). The architecture of the frame itself is similarly important in transferring as little force to the tower as possible. Although more commonly found in towers due to convenience of installation, H-frames are less effective at properly dispersing the forces exerted by swinging bells than A-frames are (Heywood & Lewis, 1914).

2.2.5 Maintaining Bells

The main parts of bells that need maintaining are the clappers, the bell frames, and the bearings used to attach the bells to the frames. Clappers need to be periodically checked to make sure they haven't become loose. Loose clappers can crack the bell or even fall off, which can damage the bell structure or even the tower (Murphy, 1992). The type of maintenance required for clappers depends on how the clappers are attached to the bells. Older bells might have clappers attached with leather linings. Once the linings become worn, they should be replaced.

Newer bells have clappers attached with metal pins that just need periodic lubrication (Church Bells, 2012). Clappers should also be painted to prevent rust (Murphy, 1992).

The second bell component that requires maintenance are the bell frames. Wooden frames need to be regularly checked for rot and replaced if necessary (Murphy, 1992). Steel frames should be cleaned and painted every 20-50 years to prevent rust (Church Bells, 2012). If bell frames break due to rot or rust, the bells would fall, which could cause significant damage to the bell and tower, and could potentially cause injury. The third component requiring maintenance is the bearings used to attach bells to bell frames. These must be kept lubricated with oil or grease, depending on the type of bearing. In the event that the bearings seize up, they must be cleaned and re-lubricated (Murphy, 1992). Finally, the bells themselves should be slightly rotated occasionally in order to prevent the clappers from causing too much wear on the surface of the bells (Church Bells, 2012).

2.3 Relevant Information for the Documentation of Bell Towers

Venice's churches are home to 136 bell towers, which form the main vertical parts of Venice's mostly flat skyline (Bell Tower, n.d.). These 136 towers are scattered throughout the city and lagoon, with 87 of them on the main island, as shown in Figure 2.6 below. Before our work, 58 of these towers have been documented by the VPC and their data stored in the VPC's database (Bove et. al, 2015; Huntley et. al, 2016). The bell towers have two different architectural styles: Roman and Standard. The vast majority of the towers in Venice are Standard towers, with a few Roman-style towers in the city as well. The Roman style bell towers are simple and less ornate, with bells exposed in a simple vela at the top. The Standard towers are much taller and follow a more conventional style.

Figure 2.6: Map of Venice Bells and Towers on Web App

2.3.1 Anatomy of Standard Tower

The Standard tower is the more common of the two styles in Venice by far. There are four main parts to the tower's anatomy: the base, shaft, belfry, and spire, each of which contributes to the overall style and integrity of the tower. Figure 2.7 shows the common layout of a Standard tower. The base is the foundation of the tower and bears the full weight of the tower. It is typically made of thicker, denser stone than that of the top of the towers. The stone is also usually less porous than the rest of the tower, so as to slow erosion from water and salt. The base may also contain tensioning supports to tether the tower down and provide stability (Huntley et. al, 2016).

The shaft of the tower is the main portion of the structure, contributing the most to the tower's height and body. It is typically made of bricks or other stone and held together with mortar. The inside of the shaft contains the stairs, ladders, ramps, or landings needed to reach the belfry (Huntley et. al, 2016).

The belfry is the part of the tower that encloses the bell chamber. This portion could be made of wood or a variety of different stones or clays. The inside contains the bell frame, typically made of either wood or steel from which the bells swing. The outsides of belfries can be decorated with carvings, statues, or other decorative elements. The belfry may be completely open or closed with windows or louvres. Most belfries are closed to protect against weather damage or prevent birds from entering and nesting. There may also be balconies or walkways around the perimeter, allowing people to walk around or look out of the tower (Huntley et. al, 2016).

Finally, there is the spire, acting as the roof of the tower. Depending on the size and height of the spire it could contain an attic of sorts above the bell chamber; access is provided by a ladder or small staircase. Common spire designs include a tapered pyramid and a dome. A finial or decorative ornament may adorn the top, serving the function of a weathervane, lightning rod or cosmetic feature (Huntley et. al, 2016).

Figure 2.7: Major Parts of the bell tower at San Marco (Huntley et al., 2016)

2.3.2 Monitoring Tower Integrity

The bell towers of Venice are essential elements of its architectural and cultural heritage (Gottardi, Marchi, Lionello, & Rossi, 2013). They are centuries-old structures, therefore it is of utmost importance to monitor their stability (Montalbano, 1989). Any accident due to lack of maintenance could potentially endanger not only the visitors and pedestrians, but also the economic life of the neighborhood. Furthermore, because of its geophysical environment, Venice is prone to earthquakes and rising water levels, thus adding to the necessity of close monitoring of the bell towers.

Structural integrity is the ability of a building to withstand the forces applied to it at a given time, and is studied in the engineering domain of "Structural Integrity and Failure." This domain of engineering focuses on making buildings structurally sound, in part by studying past failures in order to draw conclusions for the future. Furthermore, "Structural Integrity Assessment" is a general term that encompasses techniques that inspect whether the building in question is stable and provide the desired solutions for it to remain stable during its estimated building lifetime (Motarjemi & Shirzadi, 2006).

As with many centuries-old buildings, the structural integrity of Venice's bell towers has been worsened over time by several threatening conditions. Since most of the bell towers in the city are very old and made of brick, their damage mainly relates to cracks, foundation settlements, and material degradation (Gottardi et al., 2013; Rossi & Rossi, 2015). However, other environmental parameters like humidity and rising sea levels have also contributed to the their deterioration. Venetian buildings often experience recurrent floods due to rising water levels in the canals. These floods are particularly damaging because when the water evaporates, the salt remains in crystal form on the surfaces previously in contact with water. This process is described as the capillary phenomenon which causes severe damage to buildings (Capillary action of water, n.d.). Layers of Istrian stone have been used in the past to prevent water from touching the bricks, but with time and rising water levels, the damage has reached the bricks above the protective stone layers (Istrian stone, n.d.). Other solutions such as adding waterproof materials or resin between the bricks have been used. However, as in all other Venetian buildings, rising water levels and increased humidity still leave the bell towers of the city exposed to structural damage, especially affecting their foundations.

In addition to the above environmental issues, earthquakes and variations in ambient temperature affect the dynamic parameters of masonry towers in significant ways (Cavalagli et al., 2017; Gentile & Saisi, 2018). Ancient masonry bell towers like the Venetian ones are very sensitive to seismic activity, especially due to their slender shape (Cavalagli et al., 2017). In addition, increases in temperature result in increases of the natural frequencies of these structures due to the thermal expansion of materials. Freezing temperatures have the same significant effect due to the presence of ice and the freezing of the structures (Gentile & Saisi, 2018).

The age of the structures themselves is a major factor for concern, as any old building would require extensive monitoring of its exterior as well as its interior to safeguard its structural integrity.

Finally, another important factor that should be considered when monitoring the structural integrity of bell towers is that these structures are worn out due to vibrations caused by bell swinging (Gentile & Saisi, 2007; Smith & Hunt, n.d.; Ivorra et al., 2011). This is a dynamic force and may interact with the tower's natural frequencies; in addition, this force varies according to the method of bell swinging used. As a result, the forces generated due to the mass of the bell(s) cause considerable stress to a building; therefore one has to monitor for cracks in the building walls. One should keep in mind that many bell towers house multiple bells. Currently, the methods for monitoring the dynamic behaviour of bell towers consist of measuring the tower's natural frequencies with accelerometers and comparing these with the bells' oscillation frequencies (Ivorra et al., 2011). In short, monitoring involves investigating possible interactions between the tower's natural frequencies and the horizontal forces generated by bell swinging by analyzing the structure's dynamic behavior (Gentile & Saisi, 2007; Ivorra et al., 2011).

2.4 Summary

The information given above paints a clear picture of the history and importance of the bells and bell towers. It highlights their relevance in the communities and why they must be preserved. With declining church attendance, the bells and their towers can no longer be maintained through donations from mass. To preserve them, there needs to be an understanding of their construction and artistic design. We need to be able to identify the important features and characteristics such as inscriptions and decoration to have the best documentation. For the purposes of preservation, we need to know the striking methods of the bells to make sure they are being rung properly to minimize damages to the bells. This same diligence is needed with the towers as well. The importance of the towers' architecture and anatomy gives a vital look at how the towers should be documented and preserved. Knowing how to assess structural integrity in turn allows us to know what to look for to diagnose dangers to towers and potential solutions.

3. Methodology

The goal of our project is to provide a solid foundation for future restoration and reutilization of Venice's bells and bell towers by improving the VPC's collection and presentation of data. We achieved this by collecting data on the bells and towers and by presenting it in an organized and interactive way. We also assessed the accessibility of bell towers to visitors and performed research on the feasibility of a future project to directly support maintenance efforts using analysis of vibrations caused by bell swinging. The primary objectives of this project are as follows:

1. To expand the VPC catalogue of bells and bell towers.
2. To assess the safety and structural integrity of the bell towers.
3. To explore the possibility of re-utilizing the bell towers for visitation.
4. To increase public awareness of the state of the bells and bell towers.

In defining exactly what the project accomplished, it is imperative to define the scope of the work. For the purposes of this project, we focused on bells and towers that had not been previously completely documented within the mainland island of Venice as well as on conducting some of the first surveys on the island of Giudecca. We recorded dimensions, measurements, and information on the safety of bell towers; condition and activity of bells; and history of the churches and bell towers as a whole. Our research in structural integrity monitoring was limited to the tower of San Salvador, which was of particular interest to our collaborators Margherita Ganz, a PhD student in Preservation of Architectural Heritage at Politecnico di Milano, and Professor Giulio Mirabella Roberti, a structural engineer and architect, since it was affected by the 1348 Villach earthquakes. Due to its central location in the sestiere of San Marco, few steps from the Rialto Bridge, it is a popular church that many tourists visit. The bell tower dates from the 14th century. It is 40 meters tall and includes mechanical bells that are rung twice a day at specified times. This factor as well as the good condition of the bell tower were among the main reasons we decided to focus to use San Salvador as our model.

In terms of time, our documentation of bell towers took place from October 24 - November 29, and our work culminated on December 13. Further, our studies and recordings of actively rung bells was limited to the times of day the bells typically ring, which differs for every tower, but usually is between 7:00 A.M. and 12:00 A.M. (Baruffi, Spector, Boucher, and Coryea, 2012b).

3.1 Collecting Data on Bells and Towers

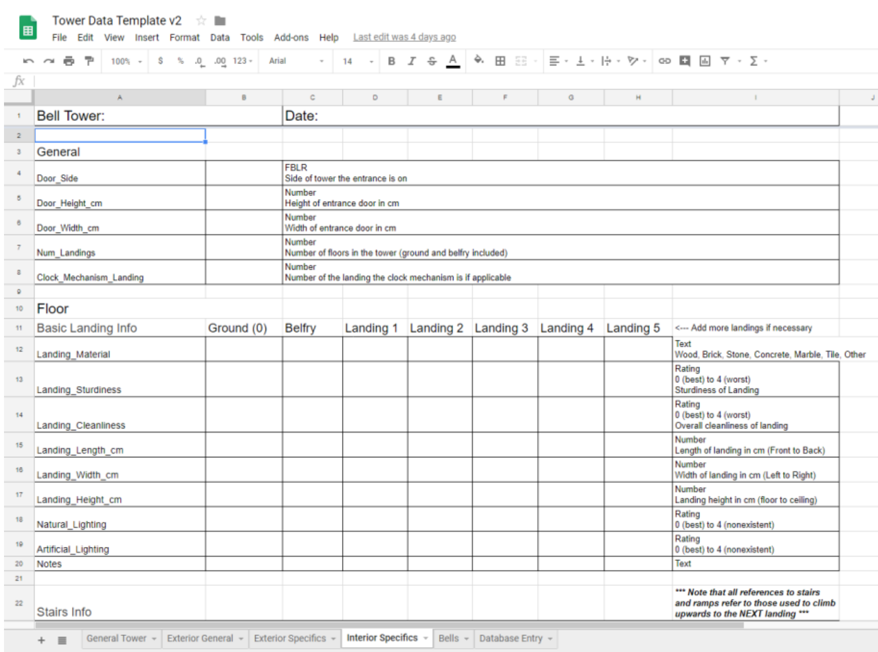
The VPC has collected data from 58 out of the 136 of the bells and bell towers of the Venetian Lagoon, thus there are many towers that still need to be visited. In addition, since the data collection was performed by multiple different teams that wanted to differentiate their work from past projects, much of the data collected differs between the towers.

To collect data on the towers, we worked with Sarah Puccio at SerenDPT to contact the local parish priests in order to identify towers to visit and schedule surveys. While visiting the towers we received help and guidance from Piero Toffolo and Michele Vianello. Piero and Michele were essential to our visits for their safety assessment, measurement tools, and wealths of knowledge in terms of architectural and structural information. They additionally translated for us at churches where the pastor did not speak English.

When surveying a tower we focused on three main areas of data collection: exterior, interior and bells. These fields included both qualitative and quantitative data including measurements, photographs, and assessments based on our judgments during the visits. All data was recorded by a team member's smartphone and a spreadsheet created on Google Sheets. Past projects created digital Google Sheets for collection, which were derived from a pen and paper system used by the projects before them. In order to improve clarity and streamline the data collection, we reorganized the past projects' Google Sheet to remove obsolete fields and provided a definition next to each data field; the glossary of terms can be found in Appendix A. The collected data was then entered into the City Knowledge console, where it was incorporated into the VPC's database for use with Venipedia and the Venice Bells Web App.

3.1.1 Streamlining the Data Collection Process

At the beginning of this project, the data collection process was extremely inefficient and disorganized. The early VPC bells projects used thorough paper forms to collect the bell and tower data, but as the data was moved into databases, much of the data became stored in fields with confusing or ambiguous names that did not adequately describe the data they held. As a result, the spreadsheets that the last project used were very difficult to use for data collection because it was often not clear what data was supposed to go where. The data collection app that the last team developed contained the exact same fields and therefore had the exact same problem as the spreadsheets. In addition, due to the database being poorly structured, the app stored the data collected in a temporary database, with a promise that the VPC would create a new database with a better structure that the data collection app would be able to interact with. While a new database was created, the data collection app was not updated to work with it, and due to time constraints we were not able to recreate it. Instead, our team read through the original paper forms and the spreadsheets of several past projects to design a new, more organized spreadsheet template for data collection that contains descriptions of what the fields mean and what type of data they should contain. An empty template of this spreadsheet is available in our drive named "Tower Data Template v2." An example of what the new spreadsheet looks like is shown below in Figure 3.1. By using this new spreadsheet, we made our data collection process more efficient and ensured that all of the collected data was correct.



Tower Data Template v2

File Edit View Insert Format Data Tools Add-ons Help Last edit was 4 days ago

	A	B	C	D	E	F	G	H	I
1	Bell Tower:		Date:						
2									
3	General								
4	Door_Side		FBLR Side of tower the entrance is on						
5	Door_Height_cm		Number Height of entrance door in cm						
6	Door_Width_cm		Number Width of entrance door in cm						
7	Num_Landings		Number Number of floors in the tower (ground and belfry included)						
8	Clock_Mechanism_Landing		Number Number of the landing the clock mechanism is if applicable						
9									
10	Floor								
11	Basic Landing Info	Ground (0)	Belfry	Landing 1	Landing 2	Landing 3	Landing 4	Landing 5	<--- Add more landings if necessary
12	Landing_Material								Text Wood, Brick, Stone, Concrete, Marble, Tile, Other
13	Landing_Sturdiness								Rating 0 (best) to 4 (worst) Sturdiness of Landing
14	Landing_Cleanliness								Rating 0 (best) to 4 (worst) Overall cleanliness of landing
15	Landing_Length_cm								Number Length of landing in cm (Front to Back)
16	Landing_Width_cm								Number Width of landing in cm (Left to Right)
17	Landing_Height_cm								Number Landing height in cm (floor to ceiling)
18	Natural_Lighting								Rating 0 (best) to 4 (nonexistent)
19	Artificial_Lighting								Rating 0 (best) to 4 (nonexistent)
20	Notes								Text
21									
22	Stairs Info								*** Note that all references to stairs and ramps refer to those used to climb upwards to the NEXT landing ***

General Tower | Exterior General | Exterior Specifics | Interior Specifics | Bells | Database Entry

Figure 3.1: Updated Data Collection Spreadsheet

3.1.2 Exterior Data Collection

The data on the exterior of the towers was focused on the architecture, decoration, and conditions of the towers. We collected 22 different data fields based off of the data collected by the 2016 WPI team, listed in Table A.1 in Appendix A. Generally, two team members surveyed the outside of the tower from as many angles as possible to collect these data. The towers were divided into four sections, namely the base, shaft, belfry and roof. Data for each section were recorded for each side of the tower in the Google Sheet whenever possible, and fields were left blank if a certain side/part of the tower was not visible. The tower and its features were also photographed for visual preservation alongside our written documentation.

To measure the tower height, we employed two methods to get an accurate height by comparing the outcomes. The first method was to use the Spike measuring tool provided to us by Prof. Carrera. This tool worked in conjunction with an app downloaded on an iPhone to create point-to-point measurements on images taken with the iPhone. We measured the distance from the observer to the base of the tower and the distance from the observer to the top of the tower. From these measurements, we used trigonometry to calculate the angle between the ground and tower and in turn the height of the tower, as shown in Figure 3.2 below. Our final method was to use a laser measure on the inside of the tower to measure the height between landings and then the height from the belfry floor to the roof. This method was slightly less effective as we were unable to measure to the very top of the roof; however, it did provide a good comparison to seeing if our other method provided reasonable results. The final height measurements were then compared with one another to see if they were similar, and finally cross referenced with a data sheet from past projects, which was provided by Piero Toffolo.

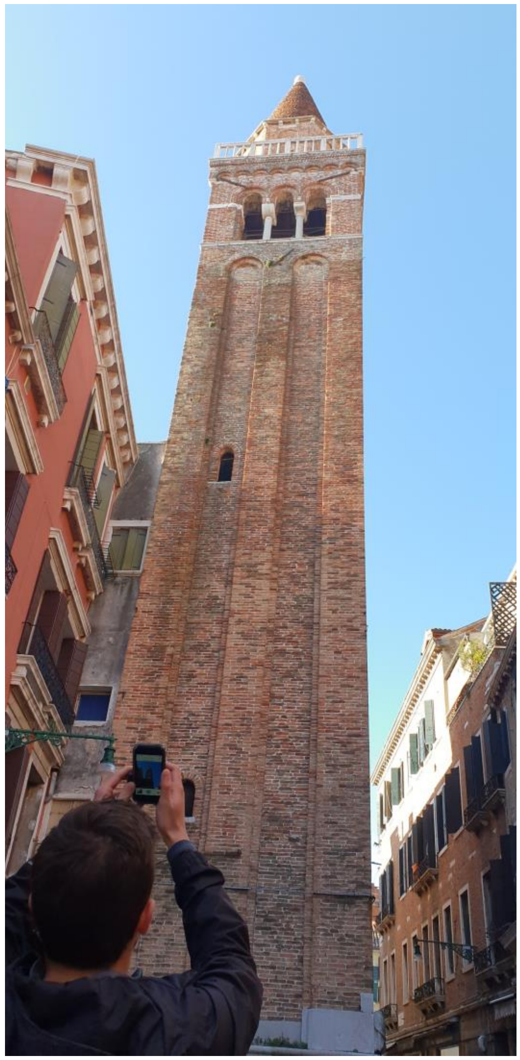


Figure 3.2: Tower Height Measurement with Spike Laser Measure

To measure the inclination and orientation of the towers we used the pre-installed compass and level apps in our smartphones. These readings were taken on all accessible sides of the tower in multiple locations on the shaft and base. Before measuring orientation, we designated the front of the tower as the side facing the same direction as the front of the church, which is the side opposite the church altar. The orientation was taken by placing the top of the phone against the wall and recording the resulting degrees and compass direction. To measure the inclination, we used the level against all of the walls in the tower throughout the base and shaft. This required multiple measurements to be averaged together because the bricks in the wall were not always level and could skew the data.

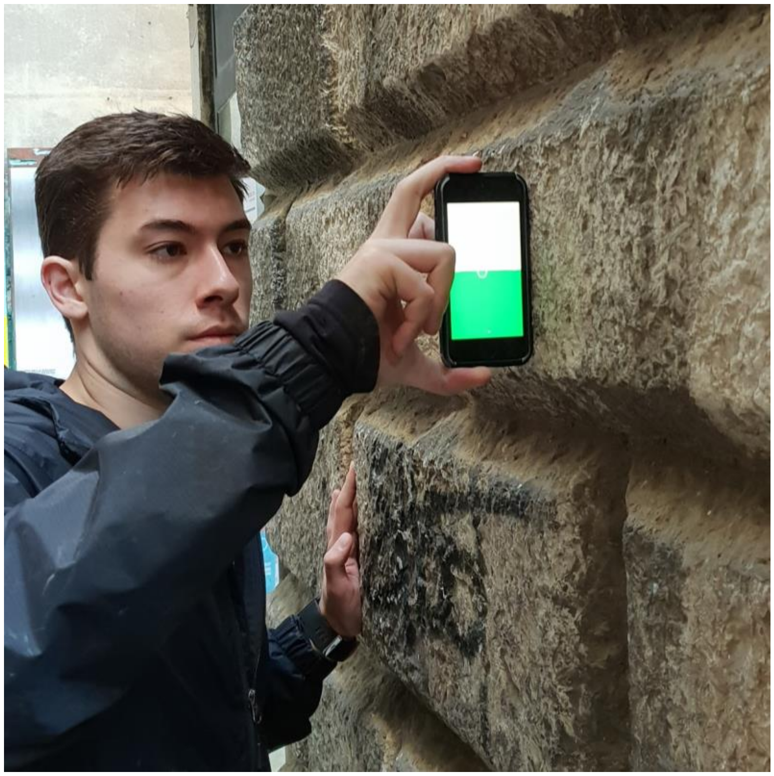


Figure 3.3: Tower Inclination Measurement

The final types of data collection we took were visual recordings of the tower's features, including the number of windows, any art or inscriptions, and signs of restoration. Visible cracks, crumbling bricks, and other signs of damage indicated that the towers might be at risk of collapse in the future. Special attention was given to the existence of metal ties or bands in the walls and visible alterations to the tower, as they indicated that the tower was damaged at some point in the past, but had since had restoration or maintenance done. All of these features were organized by which section and side of the tower they were located in. These data were purely visual as they were often on unreachable parts of the exterior of the tower.

3.1.3 Interior Data Collection

The data on the interior of the towers was focused on the decoration and dimensions of the tower interior, the dimensions and condition of the stairs, and the type and condition of the bell frame. We collected 37 different data fields based off of the data collected by the 2016 team. These data fields are listed in Table A.2 in Appendix A. The interior was divided by the landings in the tower, including the ground and belfry. All counting and qualitative measurements were made by direct inspection of the object or room in question. Subjective measurements were measured on a scale of 1-5, where 1 represents very poor condition and 5 represents very good condition. Condition measurements were documented with photographs. Size measurements were made using a tape measure and laser measure. Pictures of the internal features of the tower and its views were taken in the collection.

Figure 3.4: Interior Assessment of Tower

For quantitative data we collected the measurements of the landings traveling up the tower. Landings were defined as large, open areas that could contain more than one person at a time and were not simply larger steps in the staircases. Dimensions of landings, stairs, and windows were recorded using the laser measure or tape measure from wall to wall or stair to stair. To measure the wall thickness we required a window without glass or a screen so that we could get the tape measure out to the edge. We then measured from the inside of the tower wall to the surface outside the window to determine the wall thickness.

Qualitative data was collected with subjective judgements from the team members. Assessments of the lighting, sturdiness, and cleanliness of the stairs and landings were made on a scale of 0 to 4 with 0 being the best and 4 being the worst or nonexistent. This scale was used to maintain consistency with past projects. The fields for this collection can be seen in table A.3 within Appendix A. As can be seen in tables B.1 and B.2 of Appendix B, we also performed an overall tower assessment to judge the entire tower's cleanliness and safety, inspired the VPC's 2015 bells and bell towers project. Our goal was to continue their work in the interest of continuity, as well as use the data as an indication of usability of the towers for public visitation. Team members ascended and descended the tower in order to rate the tower in each criterium. The methods used to score the towers are described in more detail in Section 3.3.

3.1.4 Bell Data

In addition to the bell towers, we also collected data on the bells themselves. Once again, for the purposes of consistency, we focused on collecting the same data that the previous projects collected. The collected data fields are listed in Table A.4 in Appendix A.

The first type of data we collected was about the ringing of the bells. Using an audio spectrum analysis app on a smartphone, we measured the ringing frequency of the main hum, then used the frequency to calculate the musical note that the bell played. We then recorded the sound of each bell by manually swinging the clapper. If the bells still were rung normally, we also recorded the bell chorus.

Figure 3.5: Manual Swinging of the Bell Clapper

If the information was available, we also recorded the actual times the bells rang on each day of the week. Next, we collected data on the artistic design of the bell. This consisted of describing the engravings on each side of the crown, body, and lip of the bell and taking pictures of all accessible sides of the bell. After describing the engravings, we recorded the inscriptions on each side of the crown, body, and lip of the bell. If the inscriptions were unreadable, we cleaned the bells with water and brushes, then used chalk to make the letters stand out. Whenever possible, we used the inscriptions to record the date that the bell was made and the foundry that cast it. We then recorded the length and condition of the clapper as well as the way it was attached to the bell. We continued by recording if the bell was still rung and the method with which it was rung. Finally, we recorded the physical properties of the bells. Diameter, internal height, and height from the ground were recorded using a tape or laser measure, and calipers were used to measure the bell thickness. The calipers were placed at the intersection of the body and the lip of the bell, which is its thickest point, and were tightened as much as possible without scratching the surface of the bell.

Figure 3.6: Measuring Bell Diameter

Figure 3.7: Measuring Bell Thickness

The distance between the two claws was then measured with a tape measure. Next, we recorded which sides of the bell were cracked, if any. Finally, we recorded the cleanliness, discoloration, amount of chips, decoration legibility, and overall condition on a scale of 0-4, where 0 is very good and 4 is very poor, as past projects did.

3.1.5 Creation of Virtual Tours

As part of our data collection efforts, we created virtual tours of the churches and their bell towers. The tours comprise photographs spaced out at points of interest along the interior of the churches and bell towers, similar to Google Maps Street View. Each image in the tour has icons embedded in it that link to the next image. This allows viewers to progressively move through the church and tower in order to view the entire building.

The images were captured using the VPC's Ricoh Theta S 360° camera. The Ricoh Theta S captures 360° images by taking pictures with two fisheye lenses, then stitching them together in order to capture the area from all angles. The Ricoh Theta mobile app was used to retrieve the images taken by the camera. Depending on the size, we took several images from inside the churches. We then took 360° pictures on every landing going up the bell tower. We determined how many pictures to take in the belfry based on its size and visibility.

The tours themselves were created using the Kuula online software. Using Kuula's web application, we linked all of the 360° images together. Icons were embedded in each image that link to the adjacent images, as well as the main points of interest in the church, including the entrance, the altar, and the belfry. This allows users who want the entire experience to navigate through the entire church, while also allowing other users to skip directly to the "interesting" parts of the tour.

3.2 Assessing the Structural Integrity of Bell Towers

To assess the structural integrity of bell towers, we collected data related to San Salvador's bell tower's structural integrity, processed them, and assessed the feasibility of a system to do this automatically. More analytically, we focused on the forces caused by the swinging of the towers' bells, which are some of the strongest forces that belfries are subjected to (Bennati et al, 2005a,b; Ivorra & Pallares, 2006). These forces are dynamic and may interact with the bell tower's natural frequencies, which could negatively affect the tower's stability by creating resonance. Our study focused specifically on the bell tower of San Salvador. Each bell tower is unique with its own physical characteristics, placement and construction materials, so our work cannot be directly applied to other towers, however, we anticipate that our findings will encourage later projects to apply similar methodology to other bell towers in Venice. While there are case studies in other countries such as Germany, the UK, and Spain (Ivorra & Pallares, 2006; Ivorra et. al., 2011; Smith and Hunt, 2008), studies addressing the structural integrity problems of bell towers in Venice due to the dynamics of bell motion are quite rare.

To understand the impact that bells have on the structural integrity of a tower, we first calculated the tower's natural frequencies and then derived data from the bells' forces created by the inertia associated with the bell motion. in order to find their harmonics. Next, we compared these two datasets (in general, bell towers have relatively low natural frequencies and low damping coefficients). More specifically, these parameters were found by applying the iterative and incremental methodology, a widely-known methodology used in software development. The first part included retrieving geometric data of the bell tower to create a model of the San Salvador bell tower in order to find its natural frequencies through vibration analysis. For the second part, we measured the forces that the belfry was subjected to due to the swinging of bells using two low-cost accelerometers. Once we had the data, we applied the fast Fourier transform to extract the harmonics of the inertial forces due to the swinging of the bells. Once the two parts were finalized, we evaluated our results and comparisons were performed to observe the closeness of these values and evaluate the possibility of resonance.

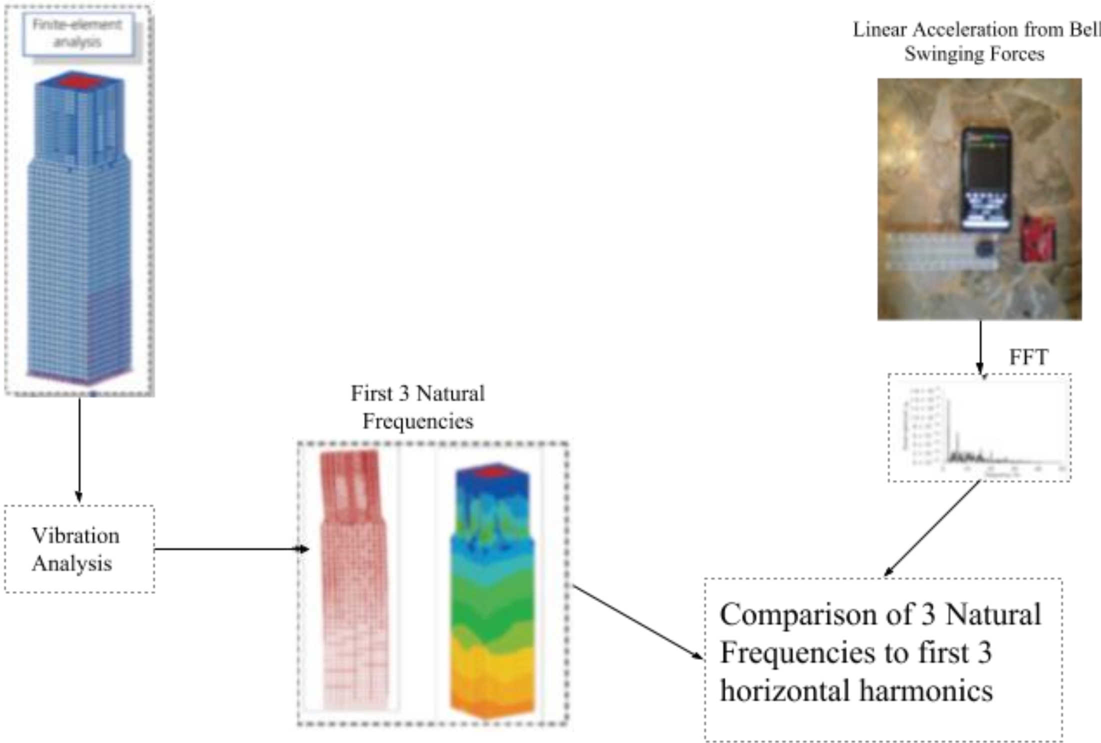


Figure 3.8: Dynamic Assessment of Inertial Forces from Bell Motion

3.2.1 Numerical Model - Modal Analysis

In order to have a reference of the main natural frequencies of the tower and its modal response, a numerical model was developed using AxisVM[1], a professional structural analysis software. We used structural drawings and measurements of the tower (Lionello, 2011), official data from the Ministry of Cultural Heritage and Activities of the Italian Republic, photos, and geometric data we collected to construct as accurate a model as possible. Once the model was complete, we were able to perform modal vibration analysis through AxisVM to extract the bell tower's first three natural frequencies. This multi-step process is shown below in Figure 3.9.

[1] https://axisvm.eu/index.html

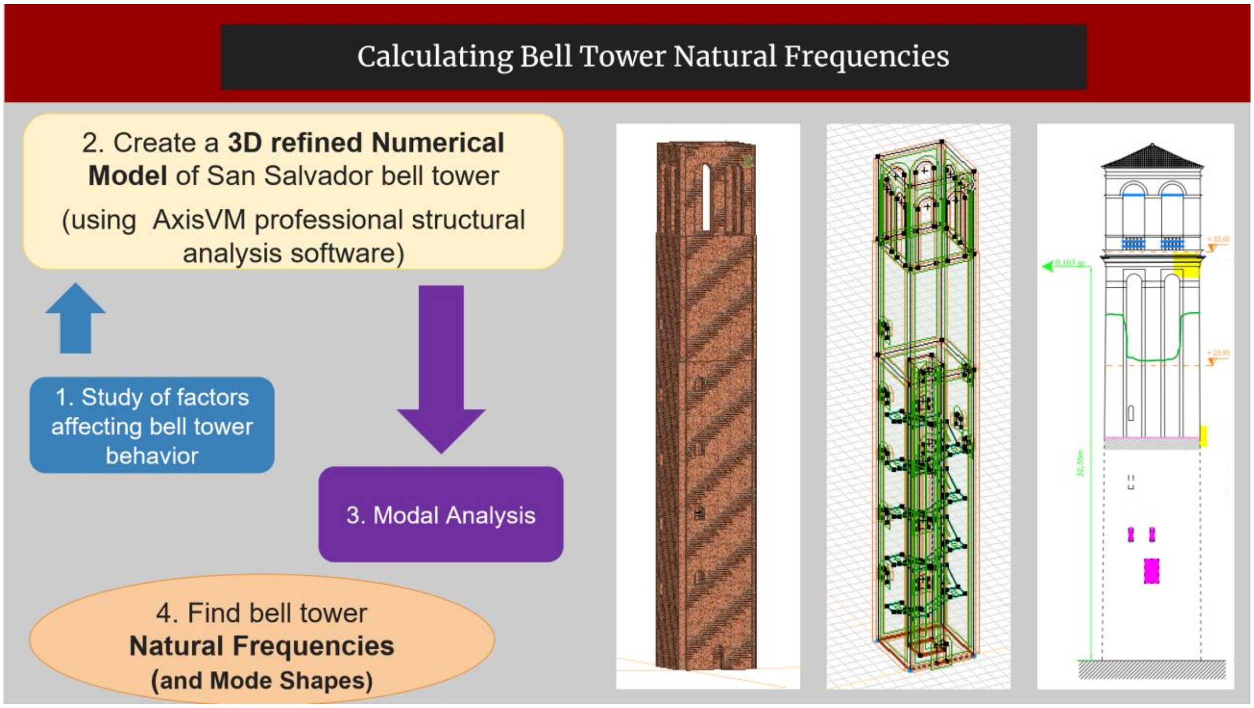


Figure 3.9: Calculation of Natural Frequencies through a Numerical Model

The first step in the process of calculating the tower's natural frequencies was to construct the model that would be used in our vibration analysis. The model was created in AxisVM by adding elements that represent the actual geometry of the tower, with guidance from Theodoros Kantzos, a civil engineer who specializes in bell towers. We created the most accurate representation of the model as was possible from the data we had available by including both the internal and external walls, the windows, the ramps, and all steps/landings. Line-to-line interfaces were used to attach the ramps to the walls as they are in reality. Additionally, we added a diaphragm at the main landing and the belfry; the diaphragm simplified the computations required by the vibration analysis by grouping elements together that would move together in reality. The ramps are shown on the left of Figure 3.10 and the diaphragm is shown on the right.

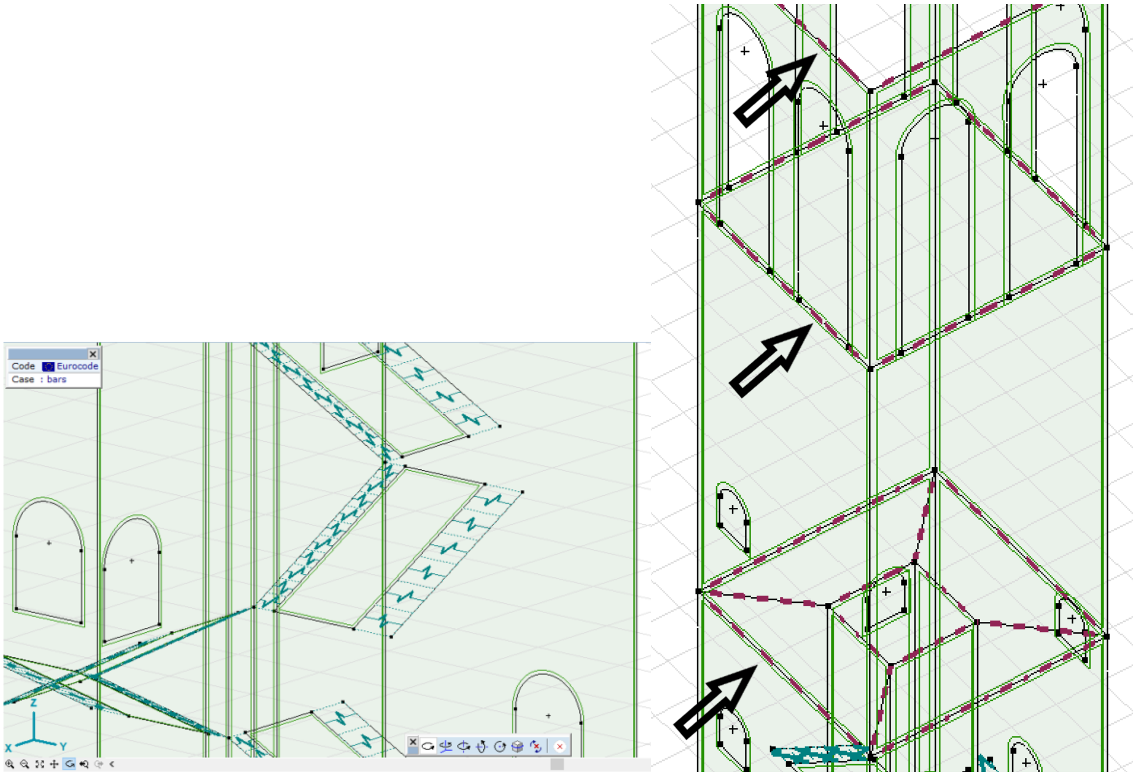


Figure 3.10: Pictures of Ramps and Diaphragms in AxisVM

Next, we added loads to the model to simulate all the weights that the tower must support. Namely, we accounted for the bells/bell frame, the landings and roof, the ramps/stairs, and the weight of the tower itself. The bell frame was represented using domain point loads wherever the frame attached to the wall. The landings and roof were represented by domain line loads around their respective perimeters. The ramps loads were similarly constructed by applying domain line loads along the top and bottom of each section of ramp. Finally, the self-weight option in AxisVM allowed us to set the load for the weight of the rest of the tower, such as the wall materials. Finally, we added line supports at the base of the tower along the perimeters of the interior and exterior walls. We specified high stiffness for these supports, except for rotation in the direction of the line. These parameters allowed the software to simulate the real behavior of the bell tower as accurately as possible in its computations. Figure 3.11 shows all the loads we used on the top and the line supports on the bottom.

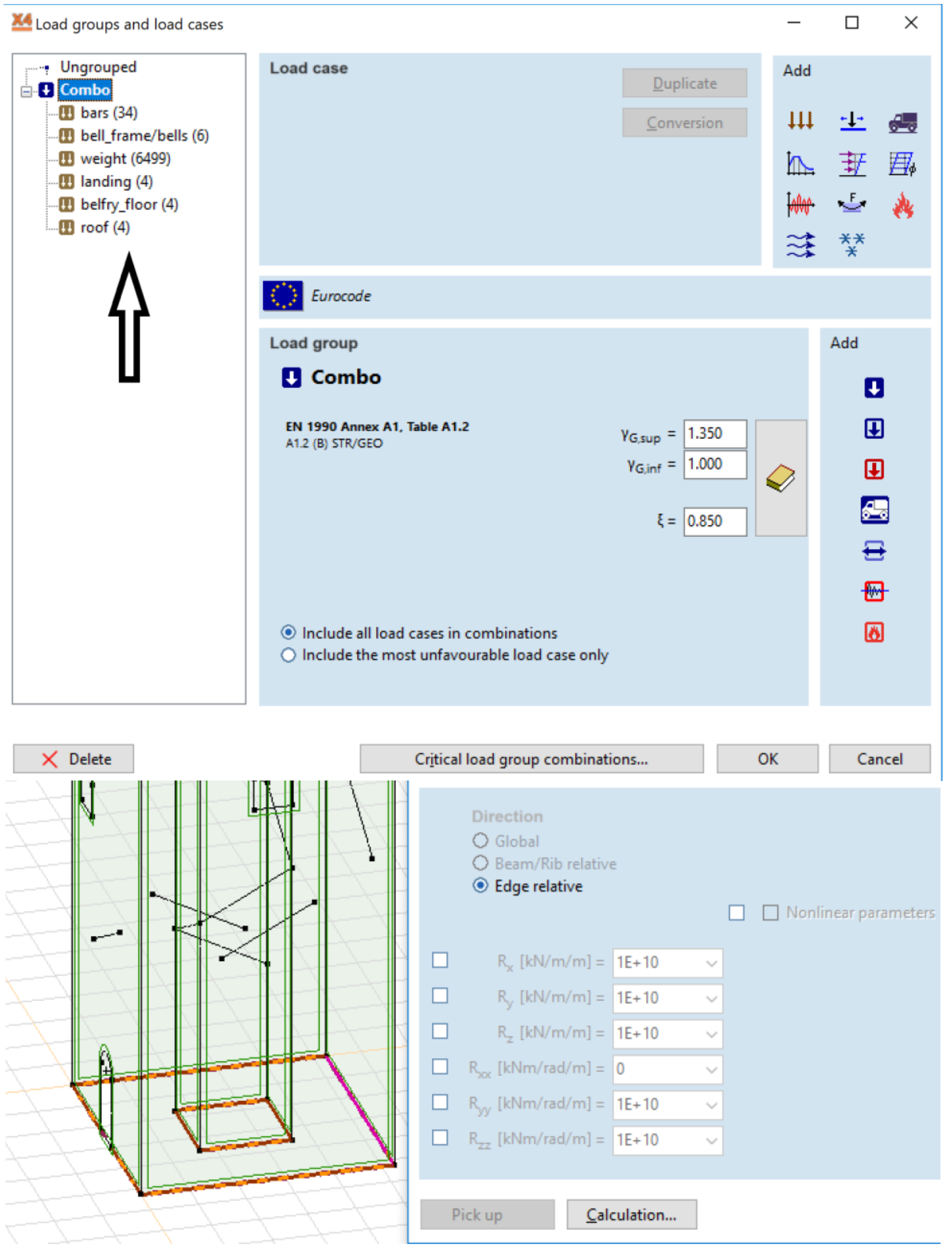


Figure 3.11: Picture of Loads and Line Supports in AxisVM

Once the basic model was complete, we performed finite element analysis to convert the geometric model into a series of small, interconnected pieces that the software can interpret in its computations. The finite element analysis used domain meshing to simulate how each element would behave under certain conditions. The lower exterior walls (thicker), upper exterior walls (thinner), interior walls, and ramps were all defined as individual domains for the domain meshing, and they used slightly different characteristics based on the average size and material of their respective elements. The option to enable calculation of domain intersections when performing the finite element analysis was selected to ensure that the separate domains we defined interacted with each other properly. Figure 3.12 shows the model after meshing.

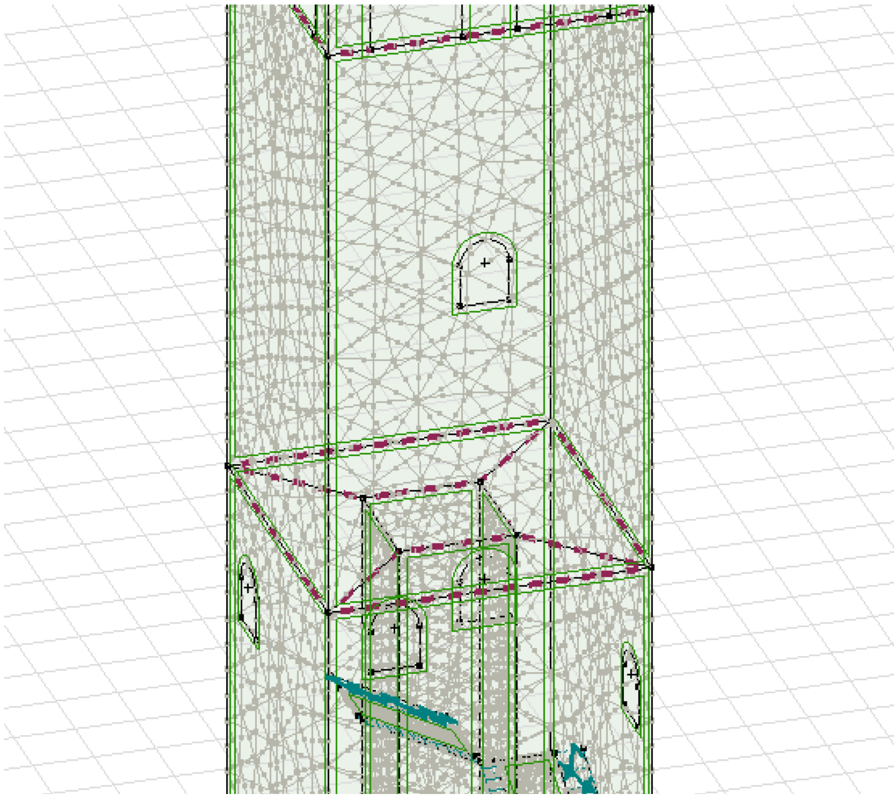


Figure 3.12: Example of Meshing in AxisVM

Finally, once the model was properly meshed, we performed a first-order modal vibrational analysis to extract the natural frequencies of the tower using AxisVM's vibration analysis tool. The analysis accounted for all mass components, which were derived from the loads during the finite element analysis as described earlier. We recorded the first 3 modes that the software calculated, which corresponded to the bell tower's first 3 natural frequencies. The settings we used in AxisVM can be seen below in Figure 3.13.

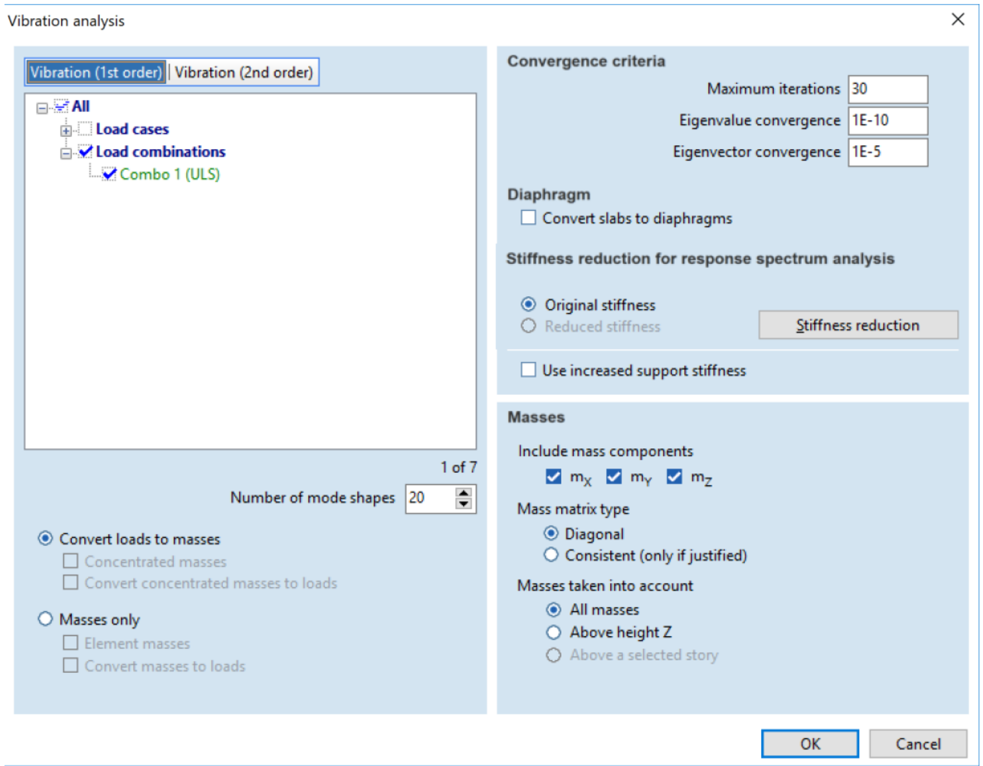


Figure 3.13: AxisVM's Vibration Analysis Interface

3.2.2 Measurement of Harmonics of Forces Caused by Bell Motion

In order to detect the harmonics of the forces generated by the bell swinging, we performed measurements of the motion of the tower using low-cost accelerometers. We measured acceleration in the belfry in the horizontal axis while the bells were swinging. With the help of Professor Giulio Mirabella Roberti, we processed the data using MATLAB to extract the harmonics of the forces caused by the swinging of bells. The fast Fourier transform was applied to the measured waveform to properly analyze the frequency spectrum of the data, and the harmonics were determined.

The first component of our observation of the bell swinging forces was the measurement of the acceleration in the belfry while the bells rang. Because we were interested in the low-frequency oscillations in the tower due to the swinging of bells rather than the acoustic vibrations transferred to the walls of the tower, we determined that measuring from the belfry floor would be as sufficient as measuring from the walls. We performed these measurements using two low-cost MEMS accelerometers, specifically the LSM6DSL and the Adafruit BNO055 Absolute

Orientation Sensor (IMU with accelerometer inside). The LSM6DSL was embedded in a mobile phone using the myFrequency app to read its output as a CSV table, and the Adafruit BNO0555 was a standalone component hooked up to a microprocessor to read its output into a laptop. Both of these accelerometers were triaxial, meaning we were able to measure both horizontal and vertical directions at the same time. We measured acceleration while the bells were swinging 4 times overall on days with a reduced level of wind and environmental vibrations: 2 tests each in 2 different locations on the belfry floor, shown below in Figure 3.14, where 1 and 2 denote the two positions of the accelerometers and the arrows denote their orientation.

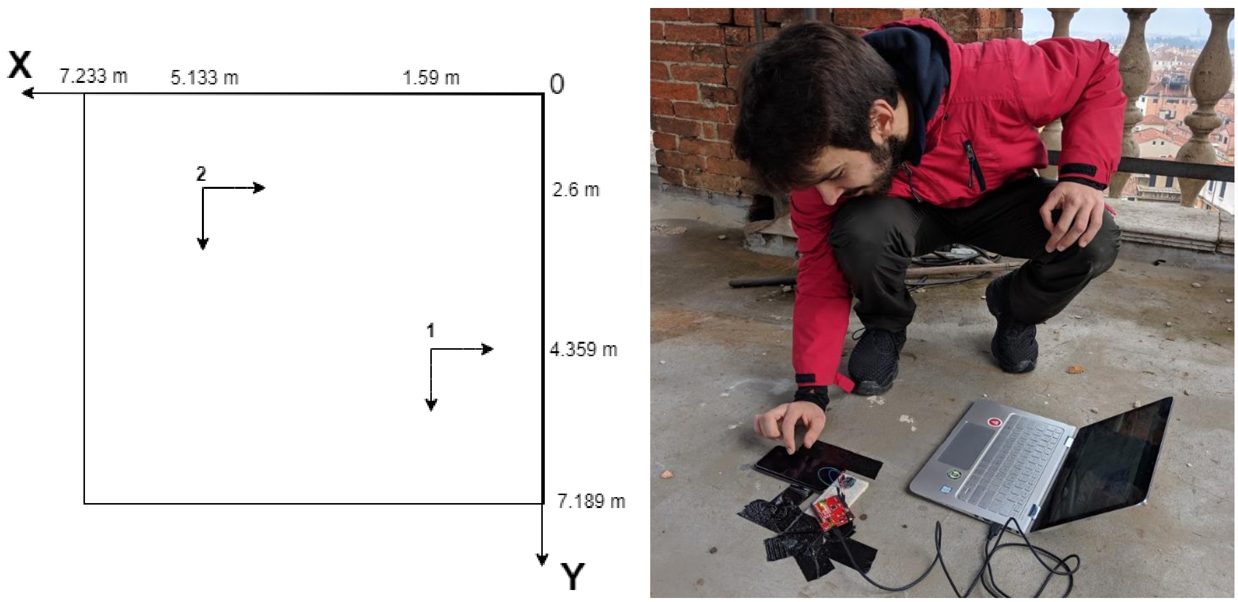


Figure 3.14: The Position of the Accelerometers

Once we collected our data, we could begin processing them. The data resulted in complex periodic signals, which we decomposed in MATLAB using the fast Fourier transform. All periodic signals can be represented by a summation of many sine waves of different frequencies using the Fourier transform, and the harmonics of the signal are found within this range of frequencies. Ideally, the harmonics would be multiples of each other that fit within the larger period, but because this is a real signal with a lot of variation rather than an ideal signal, this may not be the case. By plotting the raw acceleration data, we were able to determine the period of the overall waveform. Next, we smoothed the raw data by applying a trend filter, which accounted for small noise in the sensor and allowed us to better see the overall behavior of the signal. Also, we filtered the filtered waveform and a low pass filter to suppress the higher frequencies associated with acoustic vibrations rather than inertial forces from the bell swinging. Once we filtered the data, we applied the fast Fourier transform over the length of one period of the total waveform of the total motion caused by all bells swinging before any filters were applied, since the motion is periodic, to plot the frequency response on a logarithmic scale. The analysis was only performed on the horizontal forces because the effect of the vertical force is far less than that of the horizontal forces (Ivorra et al, 2011). From the plot of the frequency response, we identified the first 3 harmonics of the horizontal forces by observing the plots and looking for shared peaks at low frequencies. These harmonics corresponded to the first, third, and fifth harmonics of the overall total force (Ivorra et. al, 2018). The frequency spectrums before filtering can be seen below in Figure 3.15, and for comparison, an example of the frequency spectra along the X and Y axes along the X and Y axes can be seen in Figure 3.16.

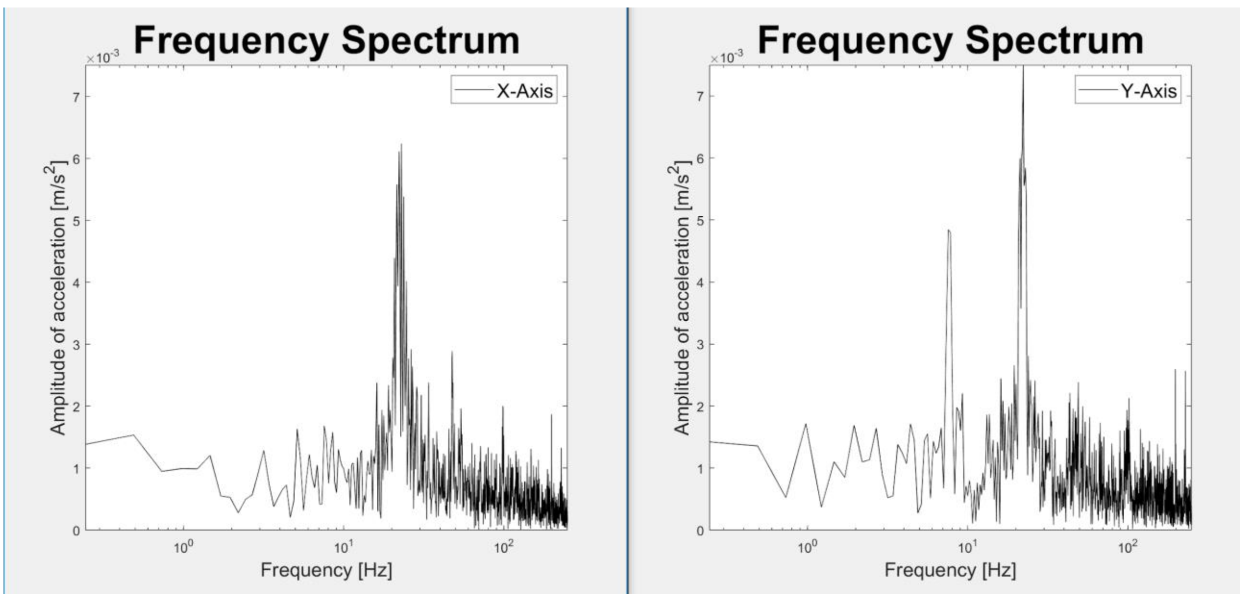


Figure 3.15: Example Frequency Spectrum Before Application of Filters

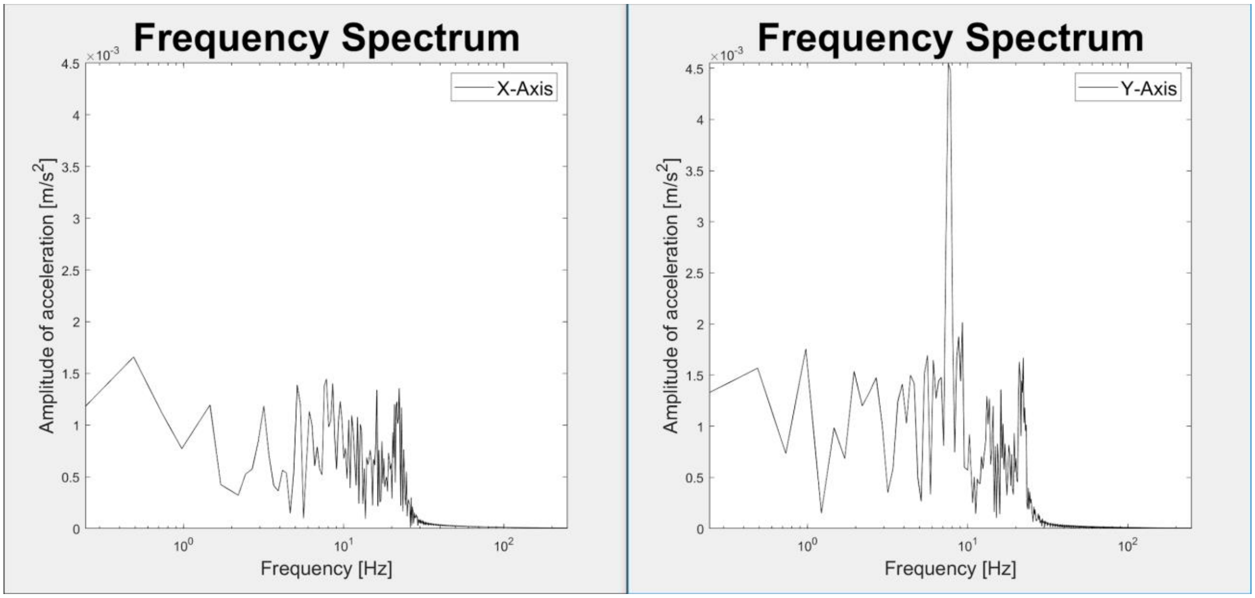


Figure 3.16: Example Frequency Spectrum After Application of Filters

3.2.3 Comparison between Natural Frequencies and Harmonics

Once we had finished collecting our two sets of data, we compared the results in an attempt to draw conclusions on the effects of forces caused by the swinging of bells and the interaction of these forces with the natural frequencies of the tower. Based on our research on previous studies of forces caused by the swinging of bells and advice from mentors, we believe that the bell swinging at San Salvador should meet the standards described in DIN4178, a standard issued by the German Institute of Standards which applies to bells using the Central European system. We found that the bells in San Salvador swing according to the Central European system because they rotate in an arc less than 180°. Thus, in accordance with DIN4178, the first three modal frequencies of the horizontal forces exerted by the swinging of bells should be separated by more than 20% from the first three natural frequencies in the structure. If our methodology produced results similar to those of other studies referencing DIN 4178, we should then be able to draw a valuable conclusion about the effects of bell swinging on the bell tower of San Salvador.

3.3 Exploring Reutilization of Bell Towers for Visitation

One of the best ways of rejuvenating Venice's bells and bell towers is by repurposing them. There are many possible ways to reuse bell towers, including using them as cell towers, alarm systems, visitor attractions, fire suppression systems, and urban farming spaces. Our project explored one of the simplest methods for repurposing bell towers by assessing their suitability for visitation. Since they are such an integral part of Venice's cultural and religious history, it is important that they are shown to people. Building on the work of past VPC projects regarding bells and towers, we explored the possibility that the towers can be used for visitation by assessing their safety and cleanliness to determine their overall visitability.

3.3.1 Assessing the Visitability of Bell Towers

To determine the visitability of the bell towers we performed on-site assessments of their safety and cleanliness during our visits. In order to assess the safety of the bell towers, we observed characteristics of the bell towers that describe the capacity of visitors in a tower and the risk of injury to those visitors. We noted several important features of the towers, including the number and condition of stairs, number and condition of landings, presence of railings, integrity of the walls and building material used for the walls and landings. Furthermore, we studied the dimensions of the belfry and the size and position of the bells to estimate how many people can enter the belfry at once, as well as examined the roof for cracks, holes, and leaks. In addition to gauging the safety, we performed similar observations relating to the cleanliness of towers. Characteristics of interest to tower cleanliness include presence of animals/animal droppings, air quality, plant growth, and rotting of wood.

3.3.2 Grading the Visitability of Bell Towers to Guests

In order to comprehensively determine the accessibility of bell towers, used a numerical scoring method to quantify our qualitative observations on safety and cleanliness. In the interest of continuity between past projects, our project and future projects, our grading system was based on of a rubric created by the 2015 VPC bell towers project. For consistency purposes, we used the same criteria from their rubric; however, we divided the criteria up into a category for safety and a category for cleanliness. Each tower received a score of 1-5 in each field, with 1 being the worst and 5 being the best. We then assigned each criterion a weight from 0 and 1 based on how important we believed that criterion was. The tower's scores in each criterion were multiplied by its respective weight, and the products were summed together to get a final score representing the tower's overall suitability for visitation, with high scores being the most suitable, and low scores being the least.

3.4 Increasing Public Awareness Through Technology

The bells and towers are key components of Venice's culture and history, but are currently underappreciated. In order to increase public awareness of the state of the bells and bell towers, we improved the Venice Bells web application implemented by previous projects and hosted at bells.veniceprojectcenter.org and developed interactive ways to advertise the bell towers to the general public. Our main contribution was significantly improving the underlying infrastructure of the app to make it more compatible with mobile browsing and easier to work with for future teams. Additionally, we improved the aesthetics and extended the set of core features of the app to deliver a more complete user experience. Finally, we devised ways to attract attention to the bells and bell towers through an eye-catching collection box and flyers advertising the web app that can be placed in churches.

3.4.1 Updates to the Web Application

The previous version of the bells.veniceprojectcenter.org web app (the "Bells App") was a functional tool, and provided a solid foundation for our work. Before our changes, the landing page of the app was a map of the Venetian Lagoon with all bell towers marked in colors corresponding to what data is available for each bell/tower. The user was able to filter the towers by various types of data fields. The user could see some basic info for a bell tower by clicking on an icon on the maps, and could then proceed to the tower's individual data page to view the full database entry. These features provided a solid foundation and were kept in our updated version of the Bells App. However, while these map features were a good starting point, we believed there was room for improvement in terms of the aesthetics, feature set, and site mapping. A complete documentation of the updated Bells App can be found in Section 4.3.

Our main contribution alongside of the new features was re-creating the Bells App using the React JavaScript library to make it more accessible on mobile browsing and easier to work with for future teams. The previous version of the app was merely satisfactory when viewed on mobile; the map and icons loaded properly, but it was difficult to zoom in on the map without resizing the whole web page. Furthermore, navigating the map with a touch screen was difficult. The previous version used the AngularJS framework, which works great for PC browsing but is not ideal on mobile platforms. Transferring the application front end to React improved its overall smoothness and functionality both on PC and mobile browsers due to the unique way it renders and updates components on the web page. Moreover, React is easier to learn than Angular, meaning that it will be easier for future projects to continue development and maintenance of the Bells App, if so desired. Because AngularJS and React are quite different in architecture and syntax, we essentially had to build the new version of the app from the ground up. Once we achieved the base functionality that the previous version had, we began to add our new features and design changes. We used the WebStorm JavaScript development environment from JetBrains to allow us to easily install the necessary JavaScript libraries and build a complete app from scratch.

Our transition to React also included a transition to a new map service under the direction of Nicola Musolino at SerenDPT. While the previous version loaded its maps from Mapbox, we have chosen to use Leaflet to load maps from OpenStreetMap instead. The latter are completely free to use, while Mapbox only allows free use up to a certain number of views each month, after which the VPC would be charged for continued use. In order to use Leaflet in conjunction with React, we used the React-Leaflet library, an open source JavaScript package that integrates Leaflet maps into React. Both Leaflet and React-Leaflet have fairly good documentation to allow future programmers to learn how to use the libraries.

3.4.2 Advertising the Venice Bells Web Application

In order for our revamped Bells App to be able to increase public awareness of the bells and bell towers, it must have an audience. In order to advertise the Bells App, we worked with Andrea Toffanello, the graphic designer at SerenDPT, to design a flyer for this Bells App. As we surveyed towers and explored the city, we noticed that many churches are open to the public during the day and it is not uncommon for passersby to briefly stop and admire the inside of a church. In an effort to drive traffic to the Bells App, the flyers are intended to be placed on bulletin boards or ticket booths of publicly accessible churches in Venice to catch the eyes of visitors.

3.4.3 Innovating Donation Collection with 3D Printing

Just as we tried to draw attention to the Bells App using on-site advertising, we attempted to draw attention to donation boxes using models of bell towers. We noticed that many of the larger publicly accessible churches in Venice have collection bins for donations for when visitors come inside to see the church. As an example of something that could be done for more churches around the city, we created a 3D model of the bell tower of San Geremia to be printed and used as a collection box. We used Solidworks to model the bell tower (Figure 4.21) and were advised by Gabriel Rodriguez, a WPI student, since none of us had any prior experience with 3D modeling. The model is hollow to hold coins, and can be separated at the bottom to empty its contents. The overall intent is that models of bell towers may catch the eyes of visitors and draw their attention to donation/collection areas.

4. Results and Analysis

Over the course of this project, we visited 11 bell towers in the sestieri of Dorsoduro, Giudecca, San Marco, Cannaregio, Santa Croce, and San Polo. During these 11 visits, we documented 38 bells, the exteriors of 10 towers, and the interiors of 9 towers. We visited the bell towers of San Geremia e Lucia, Sant'Eufemia, Ognissanti, Sant'Agnese, Redentore, San Benedetto, Sant'Andrea della Zirada, San Bartolomeo, San Salvador, San Polo, and Santa Maria Mater Domini, and are shown on a map below in Figure 4.1. We were unable to document the interior of San Geremia and Sant'Agnese, and we did not document the exterior of San Geremia. Due to the timing of our visit to San Geremia, we were unable to obtain all of the materials we needed for data collection in time, so we were unable to document anything there. However, past teams have already documented San Geremia, so its data is already in the VPC's database. We did not document the interior or bells of Sant'Agnese because there was no access to the inside of the tower, and it was a Roman style tower so there was no belfry for us to reach the bells.

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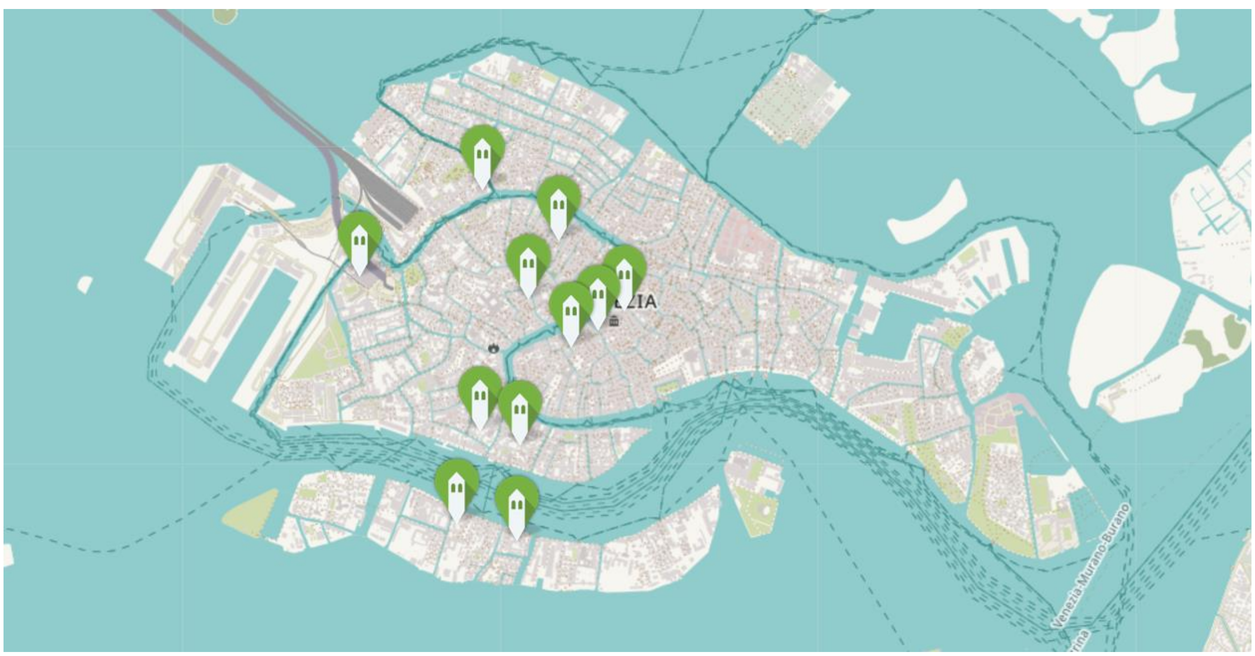

Figure 4.1: Towers Visited in 2018

4.1 Analysis of Bell Tower Interiors

The first part of the tower interiors that we analyzed were the stairs and landings. The sturdiness and cleanliness of the towers were measured to keep track of the condition of the staircases. Out of the 11 towers we visited and 9 towers whose interior we documented, 7 had very sturdy staircases, with the exceptions being Sant'Eufemia and San Polo. Sant'Eufemia's stairs were sturdy, however its landing had boards that bent slightly when we stepped on them. San Polo's staircase was also almost entirely sturdy, except for the stairs from the last landing to the belfry, which was not actually attached to anything and noticeably shook and bent while climbing it. Eight of the nine towers had fairly clean staircases which had only some dust and dirt. Sant'Andrea della Zirada was rated very poor in cleanliness due to extreme amounts of bird feathers and guano.

Next, we rated both the natural and artificial lighting in the towers. All 9 of the towers that we recorded interior data for, rated fair for natural lighting, however the rankings for artificial lighting were much more varied. No tower had good lighting, with Ognissanti and Redentore being the only two that were rated fair. San Bartolomeo, Sant'Andrea della Zirada, Sant'Eufemia, and San Salvador had poor artificial lighting, and the rest of the towers had very poor or no artificial lighting.

After all of the data collection was completed, we compiled them into a single spreadsheet and calculated weighted averages to represent their conditions. Different fields were given different weights based on their importance to the tower's overall interior condition. The fields used can be seen in Appendix C, and their weights can been seen in Appendix D. The process for assigning the tower scores is described in Appendix E. Scores in the 90s were very good, scores in the 80s were good, scores in the 70s were average, scores in the 60s were below average and finally below 60 were poor. The landing and stair sturdiness were given much higher weights than the other fields because they are imperative in order to allow the tower to be safely climbed. The final rankings are shown in Figure 4.2 below. Redentore was the only tower that was rated very good due to its extremely sturdy stone staircase and good artificial lighting. Sant'Eufemia was the only tower to be rated very poor, because its landing was not very sturdy, it had poor lighting, and it had unsturdy stairs. The rest of the towers were in fair or good condition. San Geremia was not rated because we did not collect data on its interior and Sant'Agnese was not rated because we were unable to climb it.

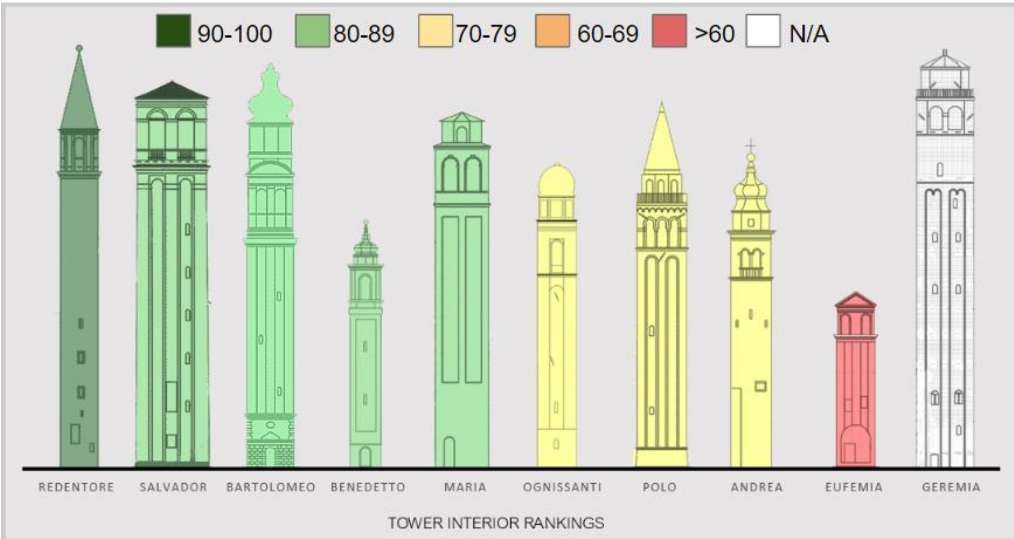

Figure 4.2: Tower Interior Rankings

4.2 Analysis of Bell Tower Exteriors

The first area of analysis for the tower exteriors was the determination of tower heights. We compared the data we took from our measurements with that of a spreadsheet provided to us by Piero Toffolo. The tallest tower we measured was Redentore at 45 meters, and the shortest tower was Sant'Agnese at 12 meters.

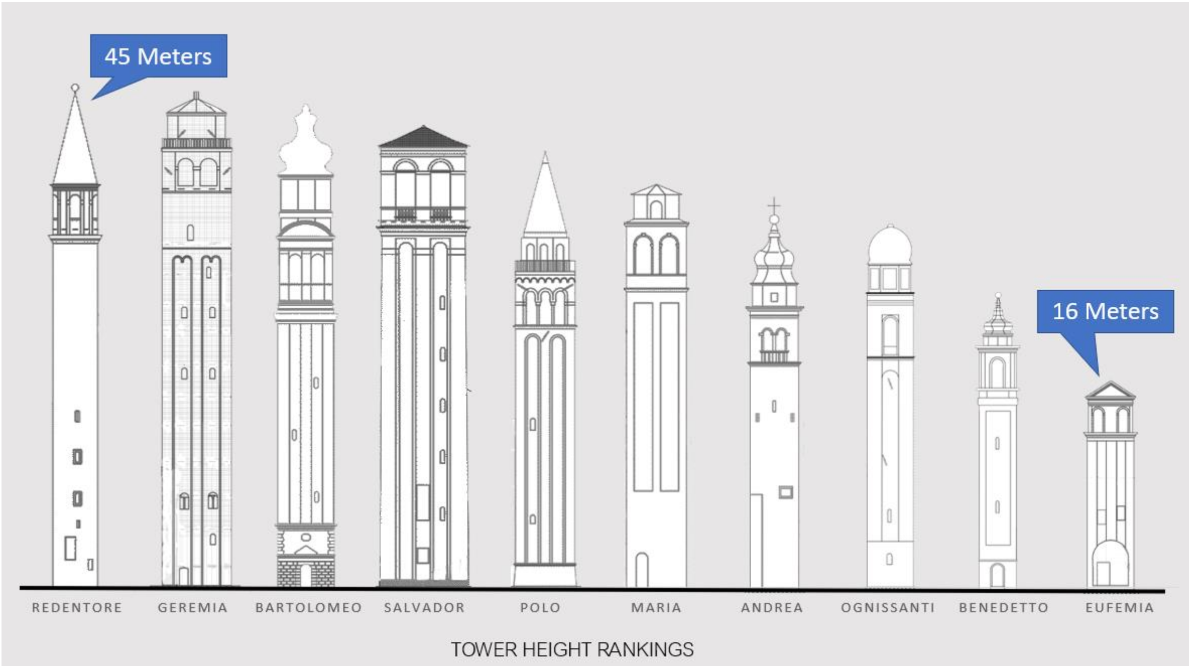

Figure 4.3: Towers Visited Ranked Tallest to Shortest (Excluding Sant'Agnese)

We then measured the towers' inclination. A visual assessment was usually good to determine if the tower was leaning, but to be more precise we used the phone level. The data was more difficult to collect since the surfaces we measured on were uneven bricks. Therefore, we measured on several surfaces on multiple parts of the tower to determine the degrees of inclination. All towers that we visited were within 3° of inclination and therefore not in danger of collapsing in any particular direction.

After careful observation of the towers exterior we determined that three towers had visible cracks or holes. Sant'Eufemia, Sant'Andrea and San Geremia all had cracks that were noticeable from the ground level. Since they were on the shaft and belfries of the tower, we could not collect data on their length or depth. Without this data we cannot arrive to any conclusions on whether or not they were detrimental to the health of the tower. Plant growth was also taken into account as the plant roots could also cause cracks not visible from the outside of the tower. Plants were seen on the shafts of San Polo and San Bartolomeo. The plant growth seen was minor and probably poses no threat to the tower in its current condition. However, if the plants grow more in number or grow in size, their roots could expand the bricks and mortar causing the tower to become unstable.

Finally, we took note of the towers with signs of restoration or rebuilding. This includes bands, ties and the addition of new bricks to the towers' existing structure. We found that 7 towers had ties or bands, which held the bricks and walls of the tower together to prevent the bricks from shifting. We found that 7 towers utilized ties and bands: Ognissanti, San Polo, San Geremia, Sant'Agnese, Sant'Andrea della Zirada, Sant'Eufemia and San Salvador. The towers that showed signs of rebuilding were recognizable by different colored or misaligned bricks in the structure. There were five towers that had been restored, namely San Geremia, San Bartolomeo, Sant'Eufemia, Sant'Andrea della Zirada, and Sant'Agnese. These features indicated whether the tower was being repaired and maintained, thus further extending their lives and preventing them from falling. These also gave us a good idea of how we could research ways to restore the towers and make plans to aid in their preservation.

After all data was collected we then put them into a weighted average. Certain fields were given more weight than others as shown in Figure 4.4. The fields used for the tower exterior can be seen in Appendix C, and all weights used for the tower exterior can been seen in Appendix D. The process for assigning the tower scores is described in appendix E. Scores in the 90s were very good, scores in the 80s were good, scores in the 70s were average, scores in the 60s were below average, and below 60 were poor. The cracks and inclination of the tower were weighted much higher because they have a higher contribution to the tower's potential collapse. As shown in Figure 4.5, eight of the eleven towers we visited had very high scores for exterior condition. The worst tower in terms of exterior condition was San Geremia, with a score of 65. Sant'Agnese was not scored because we did not have sufficient data to provide a descriptive ranking.

	A	B	C	D	E	F
1	Tower Name	Score				
2	San Salvador	90				
3	Redentore	100				
4	Sant'Andrea	85				
5	Sant'Eufemia	77.5				
6	Santa Maria	100				
7	San Bartolomeo	97.5				
8	San Benedetto	100				
9	Ognissanti	90				
10	San Polo	95				
11	Sant'Agnese	85				
12	San Geremia	65				
13						
14	San Salvador Total Ranking =	90.0				
15						
16						
17		Weight	Score	100 Scale	Average Score	Weighted Score
18	Inclination	1	4	100	100	100
19	Cracks	1	3	75	75	75
20	Plant Growth	0.25	4	100	100	25
21	Misaligned Bricks	0.25	4	100	100	25.0

Figure 4.4: Tower Exterior Weighted Average

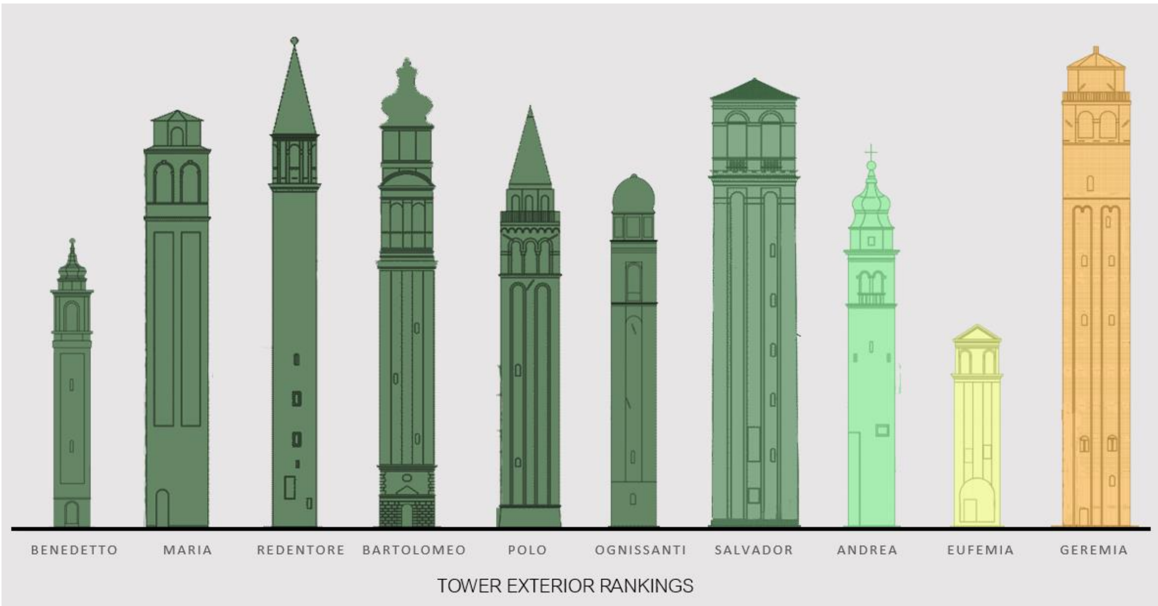

Figure 4.5: Tower Exterior Rankings

4.3 Analysis of Bells

One of the most important parts of documenting the bell towers was the documentation of their bells, as they are the entire reason for the towers' existence. We collected data on a total of 38 bells in all 9 of the towers whose interiors we were able to document, leaving out San Geremia due to time constraints and Sant'Andrea due to lack of access to the tower. However, we were unable to fully document all of the bells because some were hung too high for us to reach or blocked by bird netting. For these bells, we filled in as many fields as we were able. Every bell tower had between 2 and 6 bells, with an average number of 4. Figure 4.6 below shows the number of bells that were found in each tower.

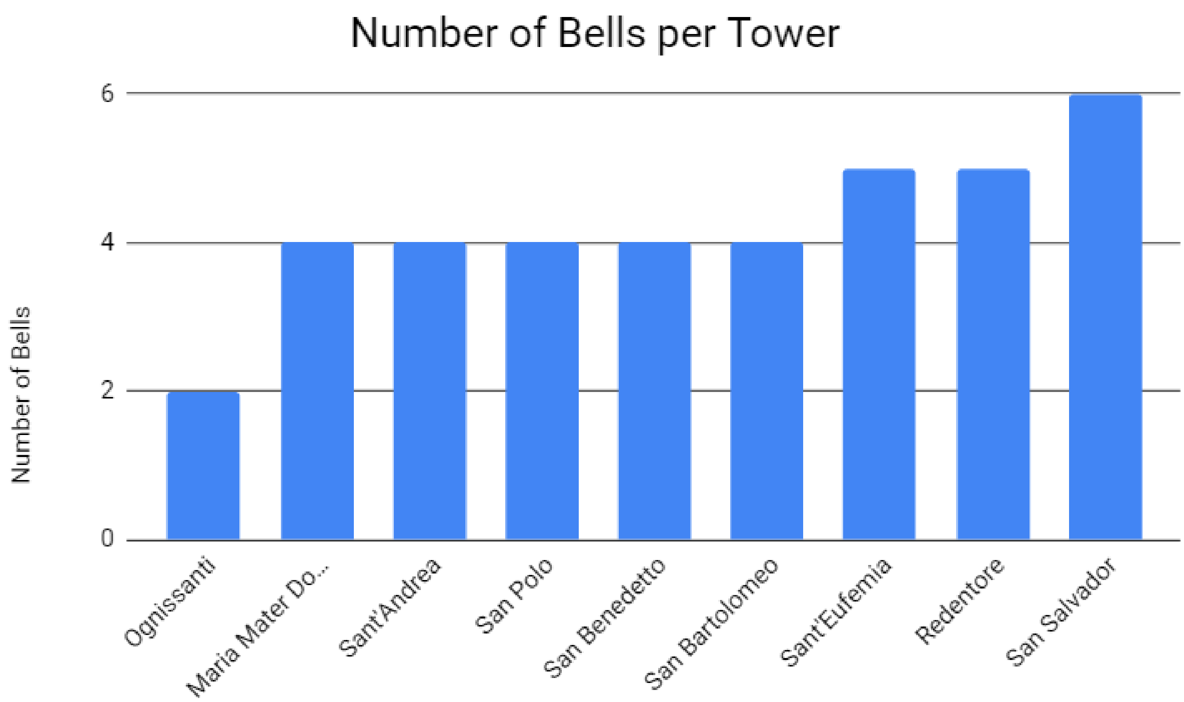

Figure 4.6: Number of Bells per Tower

We also collected data on bell sizes and in particular, their internal height, diameter, and thickness. The largest bell was bell 1 of Redentore with a diameter of 117 cm, an internal height of 93.5 cm, and a thickness of 73 mm. The thickest bell, however, was bell 2 of Redentore, which was 75 mm thick. The smallest bell was bell 4 of San Benedetto, which was 38 cm wide, 30.5 cm tall, and 25 mm thick. The average bell that we documented was 75 cm wide, 61 cm tall, and 52.5 mm thick. After collecting this type of physical data, we used the clappers to ring the bell by hand and measured the frequency at which it rang. The bells ranged from 387 to 1040 Hz, with the average being 575 Hz.

The next set of data we collected on the bells regarded their decoration. This data was important to collect for historical documentation purposes. Every single bell we documented had engravings and inscriptions on it. The average number of engravings on a bell was 8, with the most being 17 decorations on bell 1 of Sant'Andrea della Zirada and the least being 3 decorations on bell 4 of Sant'Andrea della Zirada, which was the sonello. Most of the engravings were either saints, Jesus on the crucifix, or decorative rings of vines or arches that went all the way around the bell. The average number of inscriptions on a bell was 3, with the most being 6 inscriptions on bell 5 of Redentore and the least being 1 inscription on bell 2 of Ognissanti. Most of the inscriptions were written in Latin. Many inscriptions had to do with the date and foundry in which the bell was cast. One particularly common inscription we found was "SOLI DEO HONOR ET GLORIA," which translates to "honor and glory to God alone."

Finally, we documented the condition of the bells. To do this, we collected data on the number of cracks and chips, the cleanliness and discoloration of the shell, the state of conservation, and the overall condition of the bell, as well as the condition of the clapper. None of the bells we documented had any cracks; however, all but 11 of them had some amount of chipping. 21 of the bells had ratings of good or better for cleanliness, and 11 had ratings of good or better for discoloration. In the case of discoloration, most of the rest of the bells were rated very poor. Most of the clappers were in fair condition, with several being rated as very poor. Very few clappers were actually in good condition. After this data was collected, it was put through the same weighted average system described in Appendix E, using the fields and weights listed in Appendices C and D, respectively. The results of these averages are shown in Figure 4.7 below. Most of the towers had bells with poor or very poor condition, with only San Salvador and Redentore having bells in good condition, and only San Bartolomeo in fair condition.

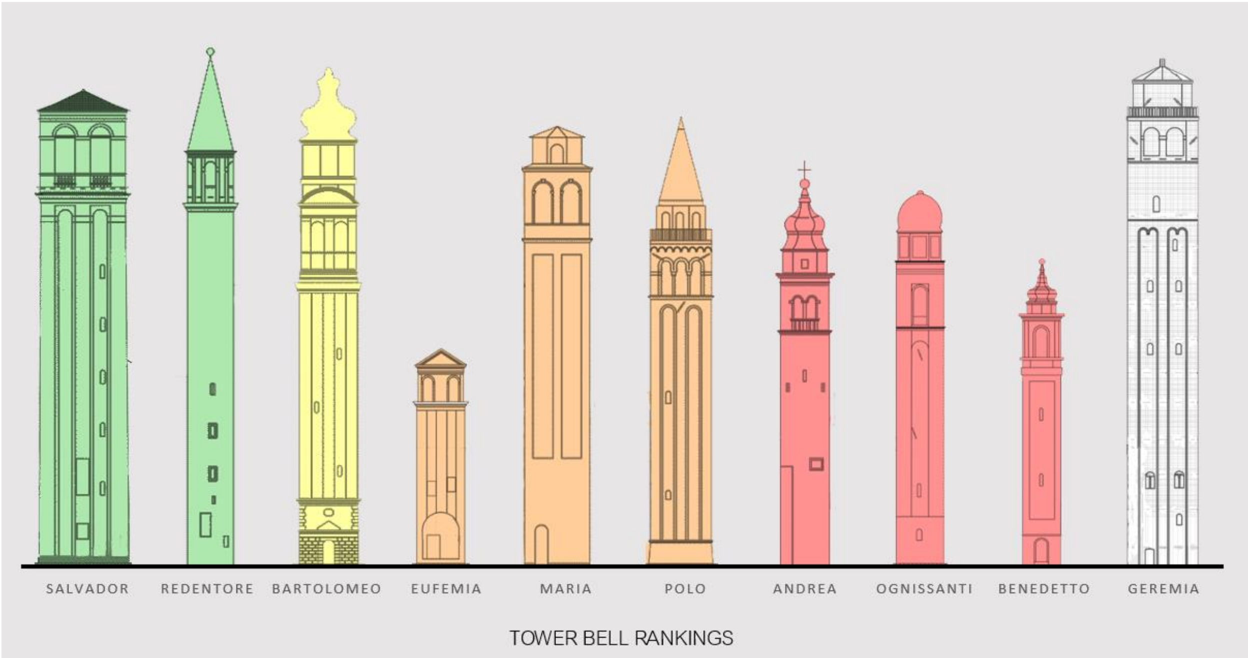

Figure 4.7: Tower Bell Rankings

4.4 Assessment of Visitability

During our data collection surveys we paid special attention to several areas that determined how suitable a tower would be for public visitation. Using the tables from Appendix B, we ranked the towers on their accessibility and cleanliness. We used a weighted average to calculate the cleanliness and accessibility of each tower. We then combined the two scores together to get an overall impression of the tower, with more emphasis on accessibility than cleanliness. Cleanliness was weighted lower because it is easier to clean the tower than to perform reconstruction in the interest of safety such as replacement of stairs or landings. The results of this assessment can be seen in Figure 4.8.

We found that two towers, San Bartolomeo and San Salvador, had exceptionally high scores. Their high scores were the result of sturdy staircases, overall cleanliness and spacious belfries. However, we decided that San Bartolomeo was not fit for visitation because it had cell tower equipment in the belfry. Sant'Eufemia was given a low score for poor access to the staircase and an unsturdy landing leading to the belfry. San Polo had a very unstable staircase leading to it's belfry, but with more repair could potentially become a very viable tower for visitation. Redentore had a very sturdy staircase, but its cramped belfry would not allow for guests to visit. Sant'Andrea had a very sturdy staircase leading to its belfry, but it was the dirtiest tower we visited by far. The tower could likely be converted to a visitation site with moderate clean up, but the views the tower offered were also some of the worse ones we observed. Ognissanti was another decent tower to visit, but the staircase was dark and the belfry landing was not very secure; the beams supporting the belfry were cracked and would need to be replaced. Santa Maria and San Benedetto scored high but the tower interiors had smaller staircases that were not lit adequately and did not offer high enough accessibility for tourists. San Geremia did not have sufficient data to score, but from our brief time there we recalled that the staircase was in poor condition.

As mentioned above, San Salvador scored high for many reasons. First of all, it had a sturdy ramp leading to the top of the tower. This allowed for a higher accessibility score as it was wide enough and requires less maintenance than a wooden staircase. There was a smaller staircase leading to the belfry near the top, but it could be easily replaced if needed. The ramp of the tower also circled a large interior shaft which could potentially fit an elevator for visitors who cannot ascend the tower on their own. Finally, the belfry of the tower was very large and spacious, and the bells hung well above head height; it could easily fit more than 10 people at a time. The view offered was spectacular as it was in the center of the city with direct line of sight to San Marco, which is significant because it is the main motive for people to ascend the tower in the first place.

14	San Salvador Total Ranking =	90.9				
15						
16						
17		Weight	Score	100 Scale	Average Score	Weighted Score
18	Roominess of Landing	2	5	100	100	200
19	Railing Presence	1	4	80	80	80
20	Landing Condition	1	4	80	80	80
21	Stair Strudiness	2	5	100	100	200
22	Integrity of Walls	0.5	5	100	100	50
23	Window Netting	0.5	4	80	80	40
24	Lighting in Shaft	0.5	2	40	40	20
25	Condition of Wood	1	4	80	80	80
26	Belfry Manuverability	1	5	100	100	100
27	Belfry Size	0.5	5	100	100	50
28	Belfry Ease of Entrance	1	5	100	100	100

Figure 4.8: Accessibility Ranking Score of San Salvador

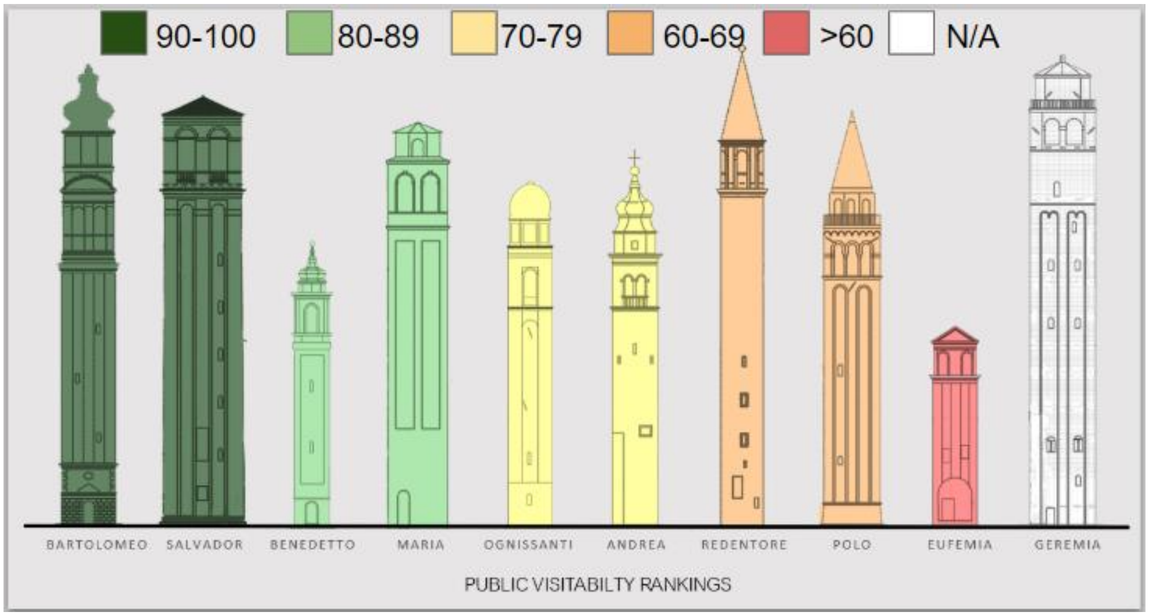

Figure 4.9: Tower Visitability Scoring (Overall Impression)

4.5 Results of Structural Analysis

As described in Section 3.2.1, we generated a 3D numerical model of the San Salvador bell tower, and successfully extracted the tower's first three natural frequencies. Figures 4.10, 4.11 and 4.12 show the results from the vibration analysis we performed on the model. In the "Isosurfaces 2D" view of the tower, each color represents the magnitude of displacement of a part of the structure. More specifically, dark red indicates greater displacement, whereas dark blue indicates a stiffer movement. All other colors are inside the range of the former and the latter. When the software performs the vibration analysis, it applies excitations of a range of frequencies to the model of the structure and simulates how the tower would behave due to each to determine critical frequencies that have an extreme reaction. These frequencies cause resonance and are the natural frequencies of the tower, which are circled in the figures below. Mode 1 was associated with bending in the east-west direction, and had a frequency of 1.35 Hz. Mode 2 was associated with bending in the north-south direction, and had a frequency of 1.36 Hz. Mode 3 was associated with torsion and twisting of the tower along the vertical axis, and had a frequency of 3.30 Hz. Together, these 3 modes gave us the first 3 natural frequencies of the bell tower.

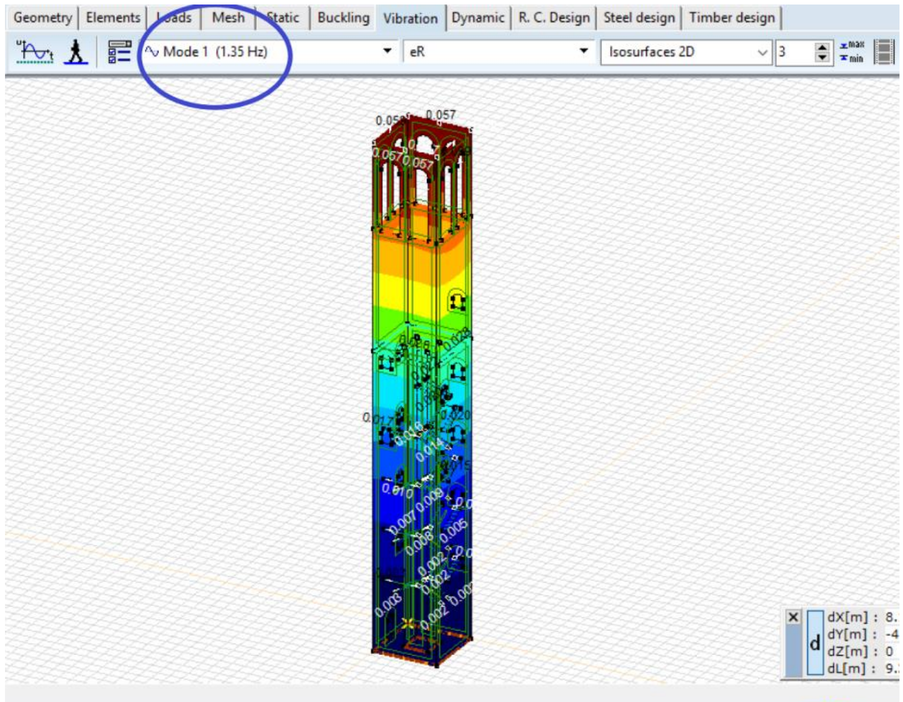

Figure 4.10: First Natural Frequency

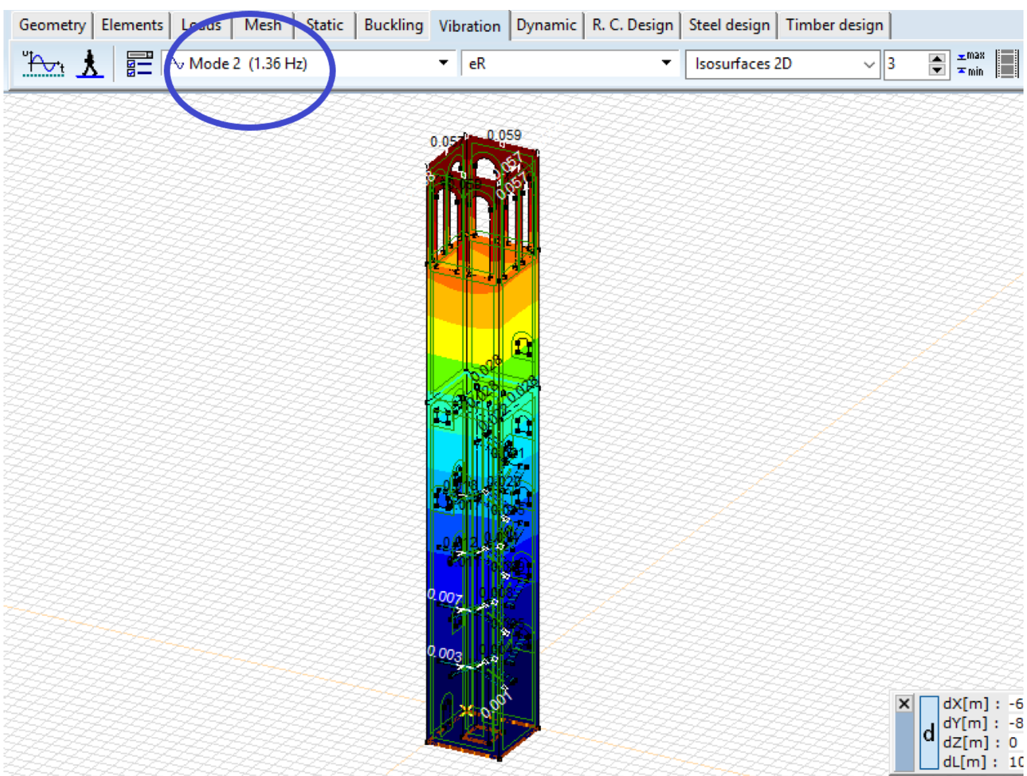

Figure 4.11: Second Natural Frequency

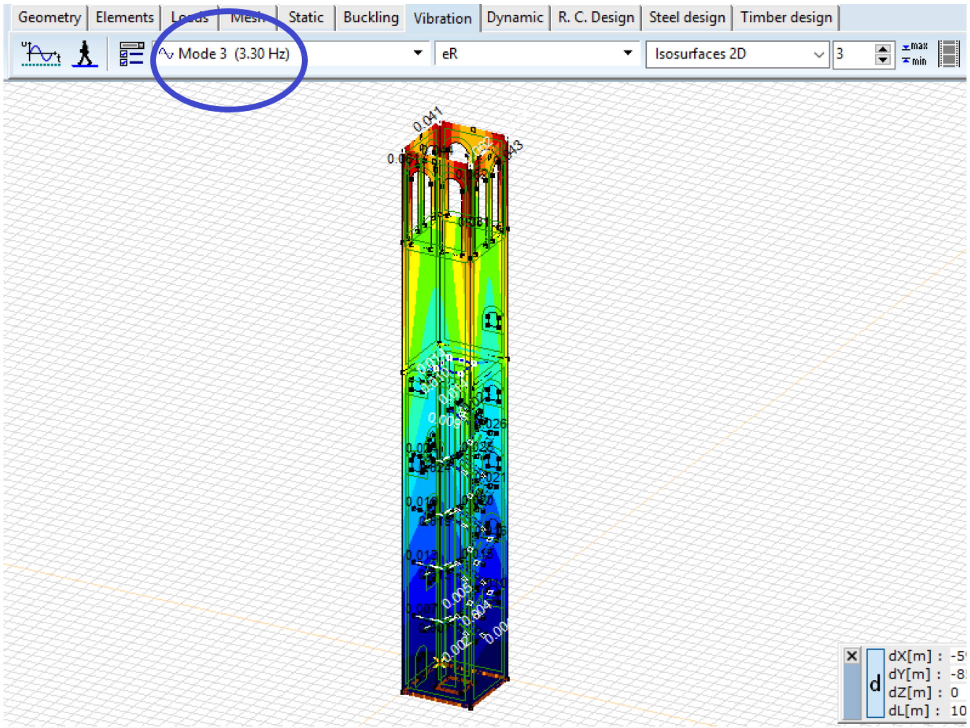

Figure 4.12: Third Natural Frequency

Additionally, we successfully measured acceleration in the belfry using our low-cost accelerometers, as high as 0.1 m/s^2 or 0.01 g in magnitude in the y-direction. As mentioned in Section 3.2, we were only interested in observing the horizontal forces because the vertical forces had a negligible effect on the tower compared to the horizontal components. Thus, we plotted the raw accelerometer data only in the x- and y-directions, ignoring the z-axis. Also, because we were only interested in the low-frequency forces exerted by the swinging of the bells and their interaction with the tower's relatively low natural frequencies, we passed the signal through a lowpass filter with a cutoff frequency of 5 Hz. The filter effectively removed noise from the higher-frequency acoustic vibrations to better observe the frequencies of interest. The plot of the raw accelerometer data that we used to determine the period is shown below in Figure 4.13. By zooming in on the plot of the total waveform before any processing and measuring the time between peaks, we determined the period to be approximately 1.24 s.

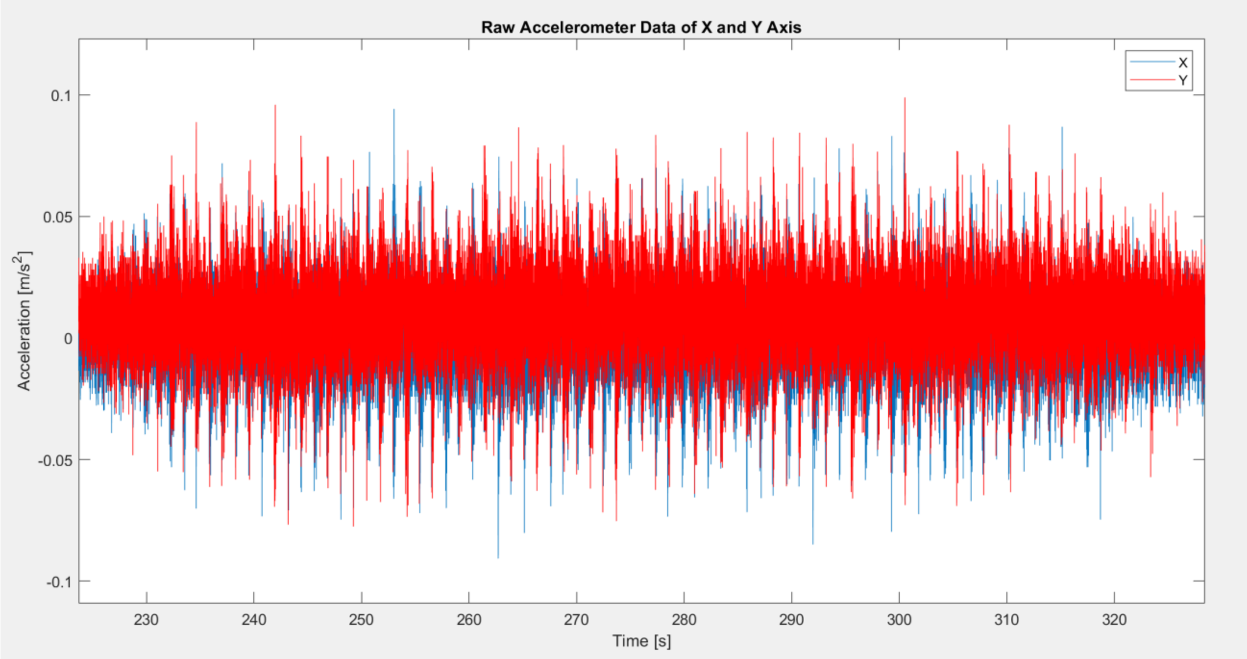

Figure 4.13: Plot of Raw Acceleration Over Time

We were then able to perform the fast Fourier transform on the filtered data over the period of interest. Because the behavior of the waveform was widely dynamic over the entire time domain, we chose a period in the waveform in which the bells were swinging with the most movement in order to measure the system response at the most impactful point. The Fourier analysis allowed us to plot the frequency response of the system in both the x-direction (left) and y-directions (right), shown in Figure 4.14. Using this plot, we extracted the first three horizontal harmonics found between the x- and y-components, which together composed the horizontal force that we were interested in. The peaks on the plot of the frequency response represent the harmonics in a given direction, circled and labeled on the graph. The forces in the x- and y-direction showed the same harmonics (with the exception of the second harmonic, which only appeared in the y-component), leading us to believe that these are the true harmonics of the horizontal forces caused by the bell swinging. The fact that the second harmonic did not show up in the x-direction can likely be attributed to the fact that the bells of San Salvador all swing in the y-direction. The three horizontal harmonics observed were 0.4888, 0.9775, and 1.468 Hz; which are the first three harmonics of the horizontal force.

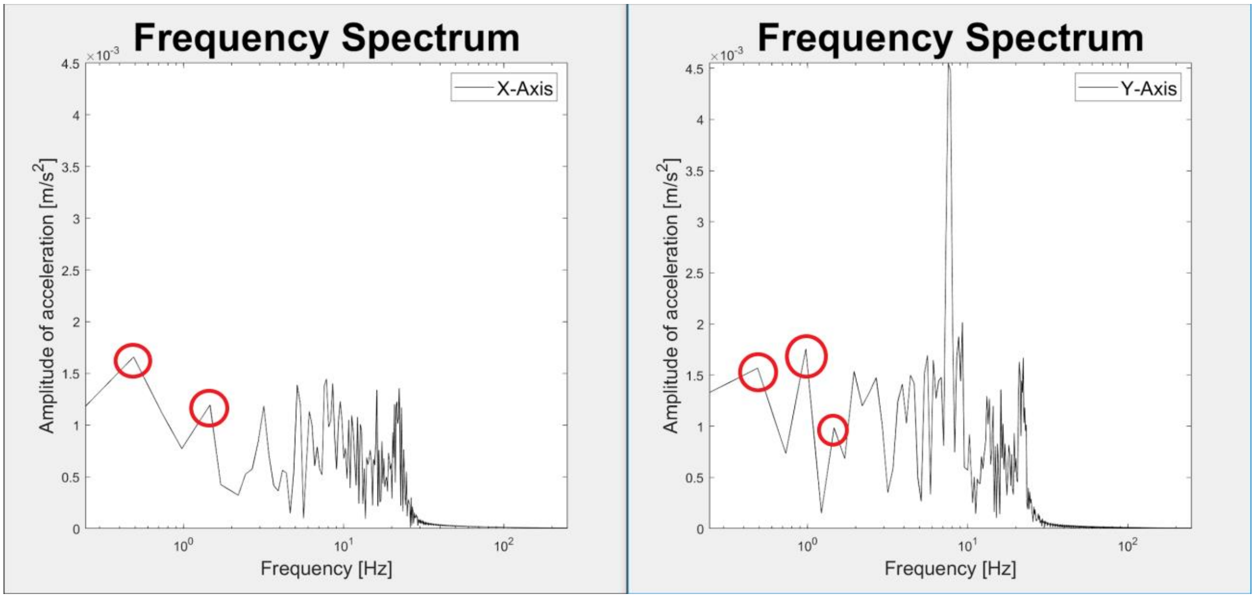

Figure 4.14: Frequency Spectra in the x- and y-directions

Comparison of the three natural frequencies of the tower and the first three harmonics of the horizontal forces show that the forces from the swinging of the bells do not meet all the criteria of DIN 4178. The results and comparison are presented below in Table 4.1. It was observed that the first two harmonics of 0.4888 and 0.9775 Hz are well outside the 80-120% intolerance ranges of all three natural frequencies. However, the third horizontal harmonic of 1.466 Hz does fall within the intolerance ranges of the first and second natural frequencies.

Table 4.1: Natural Frequencies and Harmonics of Bell Swinging Forces

	Natural Frequency (Hz)	Intolerance Range (Hz)	Harmonics (Hz)
First	1.35	1.08 - 1.62	0.4888
Second	1.36	1.09 - 1.63	0.9775
Third	3.30	2.64 - 3.96	1.466

4.6 Updates to the Venice Bells Web App

The updated version of the Bells App that we created greatly improves upon the previous version. The most impactful change is the transition to the React JavaScript framework. Additionally, the new version comes with an expanded set of features to explore the bells and towers, including new ways to sort the data and updated layouts of existing pages. Finally, an updated sitemap, shown in Figure 4.15 below, has improved the flow of the website to make it feel like a more complete experience. This section will outline the flow between different parts of the website and explain the overall functionality.

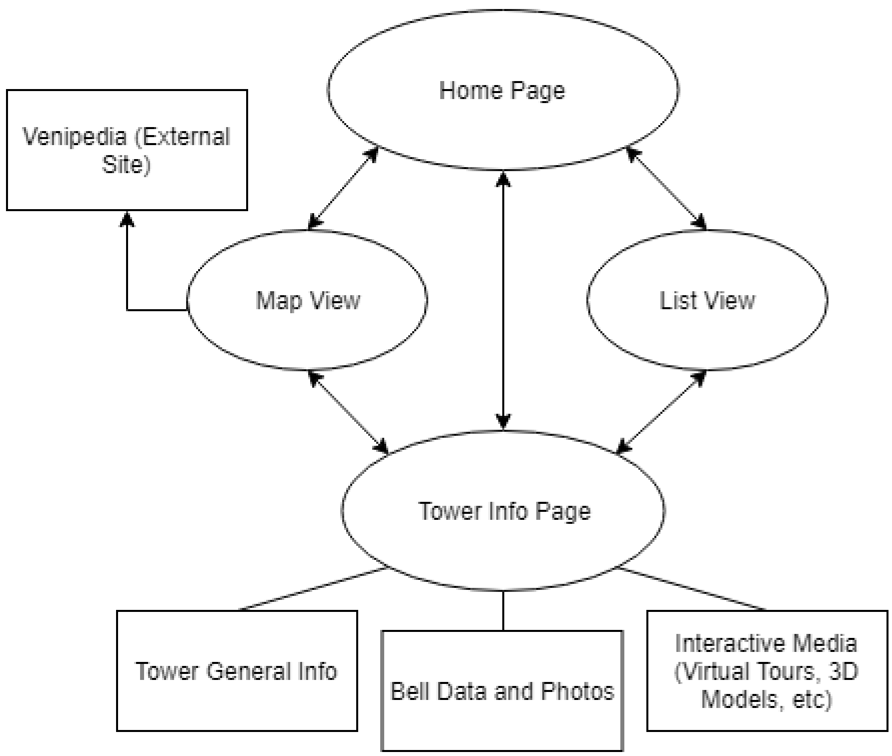

Figure 4.15: Sitemap of the New Bells App

4.6.1 Moving from AngularJS to React

The biggest and most impactful change we made to the Bells App was the transition from an AngularJS framework used in the last version to the React framework. React excels at rendering fast and clean front-end clients by maintaining a virtual DOM. This allows it to only re-render elements of the web page that have changed, while traditional front-end rendering such as what is used in Angular must re-render all elements when any element changes. As a result, the new version of the website can render a cleaner aesthetic quicker than the previous version. Furthermore, the transition to React improves the scalability of the website for the future. We found that React was significantly easier to learn than AngularJS, which makes it easier for future VPC projects to expand on our work, especially if they have little prior experience programming in JavaScript.

4.6.2 New Homepage

The first addition we made to the Bells App is a homepage that the user sees when they first access the website, shown in Figure 4.16 below. The previous version directed the user straight to the map page, which made sense in the past version because the map was the only way to view the different towers. However, with the addition of the list view to complement the map, we believed there needed to be some sort of introduction page. This homepage allows the user to choose either the map or list view to see all the different towers. The homepage can be returned to at any time by clicking the Venice Bells logo in the navigation bar at the top of the screen. Also contained in the navigation bar is the search bar, a function that was intended to be implemented in the past. The previous version had a search bar, but it did not actually work at all. We have fully implemented the search feature so that the user can go to a specific tower without having to find it on the map or list. The search bar is seen on the top right of Figure 4.16.

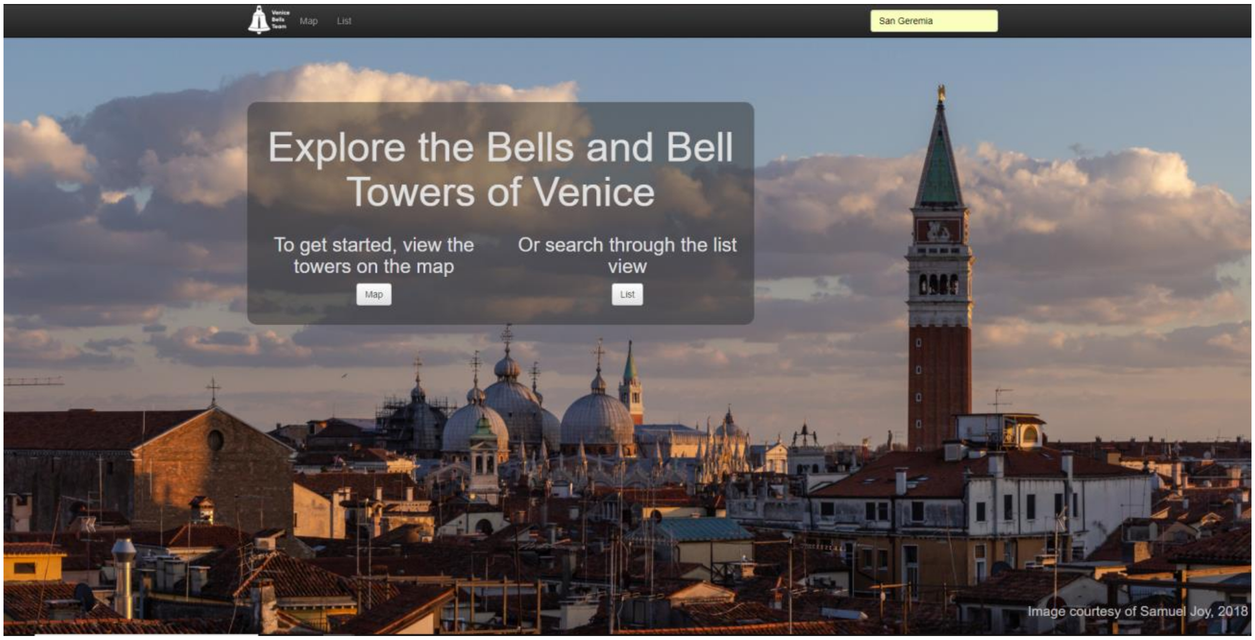

Figure 4.16: Home Page

4.6.3 Updated Map View

In addition to adding the homepage, we updated the map that serves as one of the two main ways to view the towers. As detailed in Section 3.4.2, we successfully transitioned from Mapbox to OpenStreetMap using React-Leaflet, allowing for unlimited free use of the maps without worry of ever being charged for overuse. We also moved the legend to the left side of the screen for all sorting methods; the previous version rendered it in the right corner, except when sorting by sestiere, when it was moved to the left. For the sorting, we tweaked it slightly but kept the options mostly similar; the only difference is that the "Available Data" sorting now displays which towers have interactive media rather than panoramic views from the top to better flaunt the experience of visiting a bell tower. Finally, we updated the tower icons and popups to fit with the more modern aesthetic of the website. The map page can be seen below in Figure 4.17. The drop down menu in the top right controls the sorting of the towers, and the legend is shown on the left of the screen. Clicking on a tower icon will bring up a popup containing basic information about that tower, including name, sestiere, and a picture of the tower if available. From here the user can choose to either go to the external Venipedia page for that tower, or be taken to our tower info page.

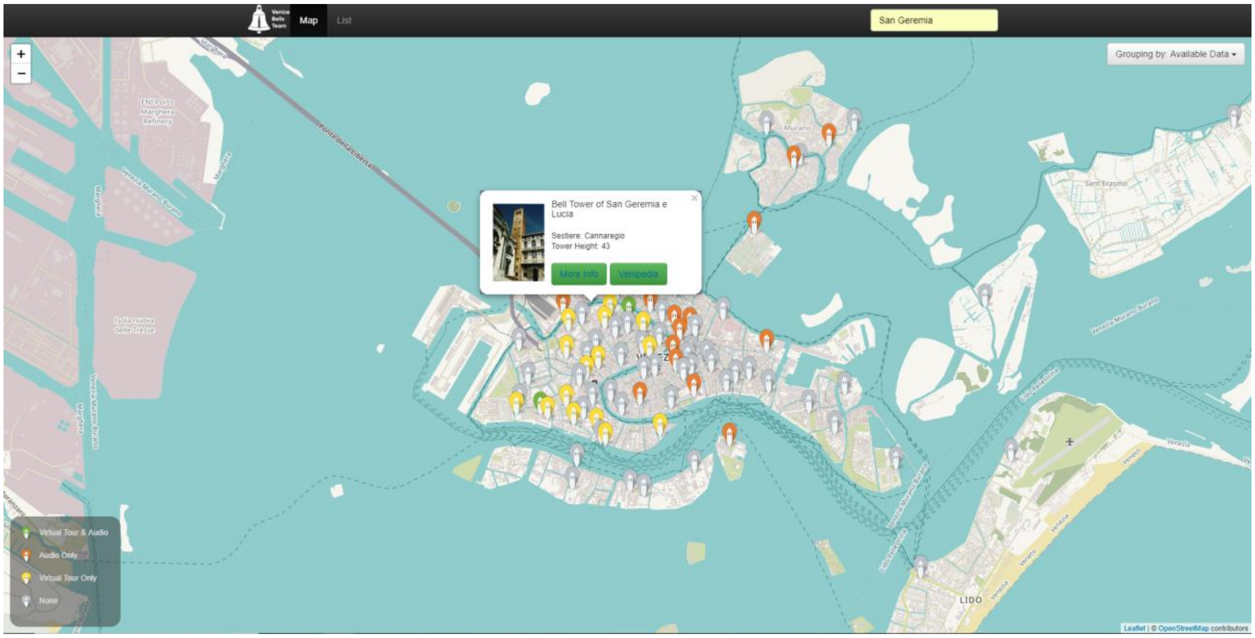

Figure 4.17: Map Page

4.6.4 New List View

Another big addition to the Bells App is the list view to see all towers in more of a database-like setting. The use can access the list view either from the homepage or the navigation bar at the top. When the user first loads the list view page, shown below in Figure 4.18, they will see all towers in the database in descending alphabetical order. Each entry in the list shows the name of the tower, a picture of the tower if available, and some basic information from the database. On the left of the main list is a sidebar containing checkboxes that the user can use to sort and filter the list of towers, allowing them to see specific sets of data. The list entries can be filtered by sestiere, documentation, frame type/material, and availability of photos, interactive media, and church history. They can then be sorted in ascending or descending order by common name, height, number of bells, number of steps (or bad steps), number of landings, construction year, safety, accessibility, overall condition, and suitability for public visitation. Clicking on the name of the tower takes the user to our tower info page, and the user can return to the list view from anywhere on the site using the navigation bar at the top of the screen.

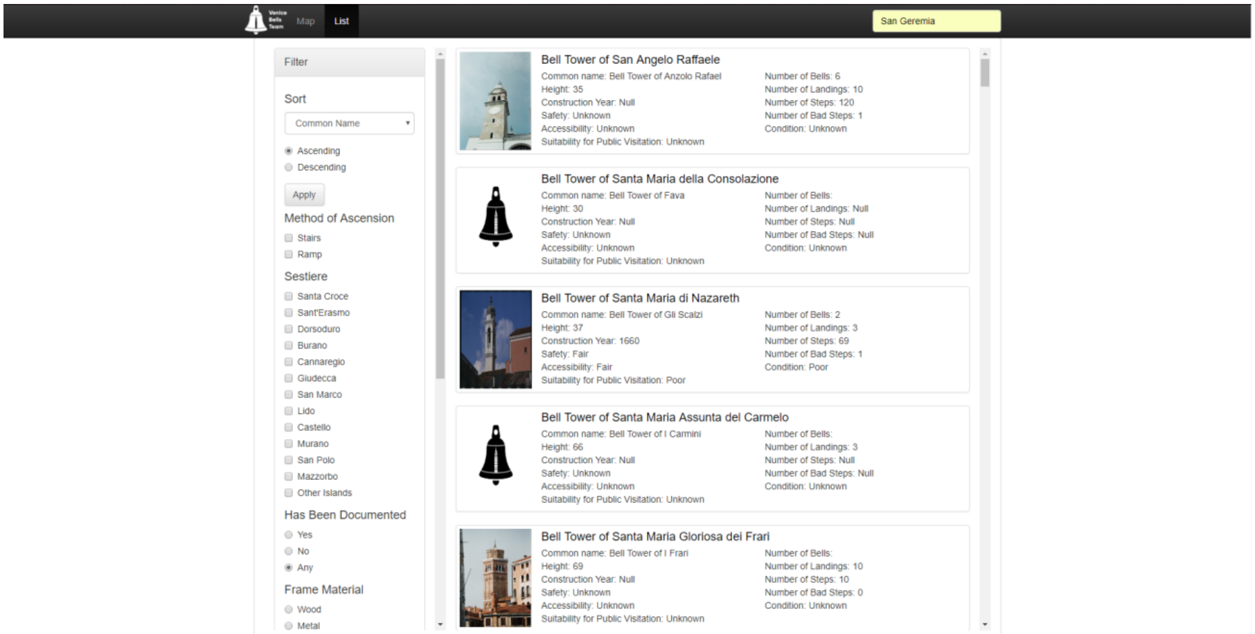

Figure 4.18: List Page

4.6.5 Updated Tower Info Page

Finally, we updated the layout of the tower info page to better fit with our more modern aesthetic. The old tower page had one tab that displayed all of the available data for the tower in one list, and a tab for whatever interactive media was available. We have updated the layout to categorize all the available data, as can be seen below in Figure 4.19. We added the basic information about the tower that shows up in the map popups and list view to the sidebar, and the sidebar is visible no matter which tab the user is on. The tab that the user lands on is the tower data page, where the user can see all available data about the bell tower itself; this data is also organized into categories to better display them.

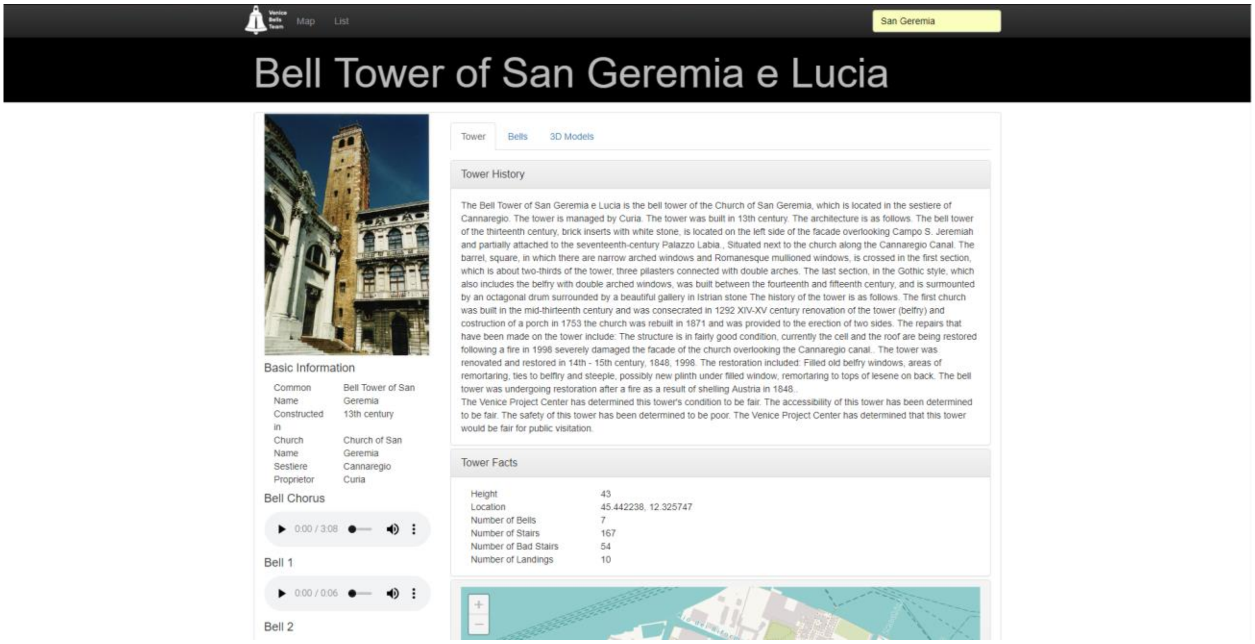

Figure 4.19: Tower Page

Next, we added a tab dedicated to viewing the bells, shown below in Figure 4.20, which did not exist in the previous version of the app. In the bells tab, the user can see photos and statistics about each bell in the tower, as well as hear them ring (if they have been documented). The photos are displayed in a carousel of images for each bell that the user can click through. Underneath each photo carousel are some brief statistics of each bell, and each bell's sound recording. At the top of the page, a diagram of the layout of the belfry is shown if it exists. Finally, additional tabs for virtual media (Matterport tours, virtual tours, 3D models, etc.) are generated based on which types, if any, are available for the given tower. Under this tab, any available virtual media is embedded so that the user can interact with it.

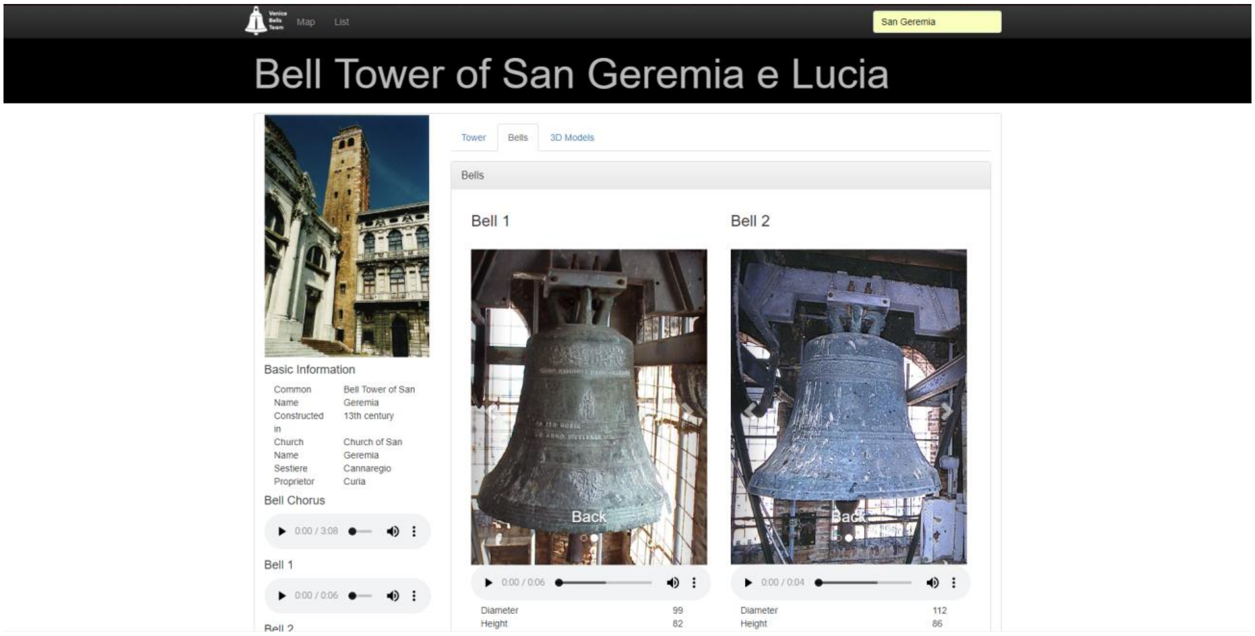

Figure 4.20: Bells Tab

4.6.6 Innovative Means of Advertisement

As a means to try and attract a larger audience to the Bells App, we developed two ways to promote the website. The first is the use of a flashy advertisement flyer that can be distributed to the churches of Venice. The second is the design of a 3D model of a bell tower which can be used as a coin collection box.

The advertising flyer is intended to be handed out to publicly accessible churches in Venice, and it can be hung on bulletin boards, on ticket booths, or next to collection bins where it can be easily seen by visitors. This flyer contains a QR code that can be scanned with a mobile phone to take visitors to the Bells App on their phone. It also provides a brief overview of some of the features that the Bells App offers, and presents the URL of the website so that visitors can visit the website from their computer. The completed flyer can be seen below in Figure 4.21.

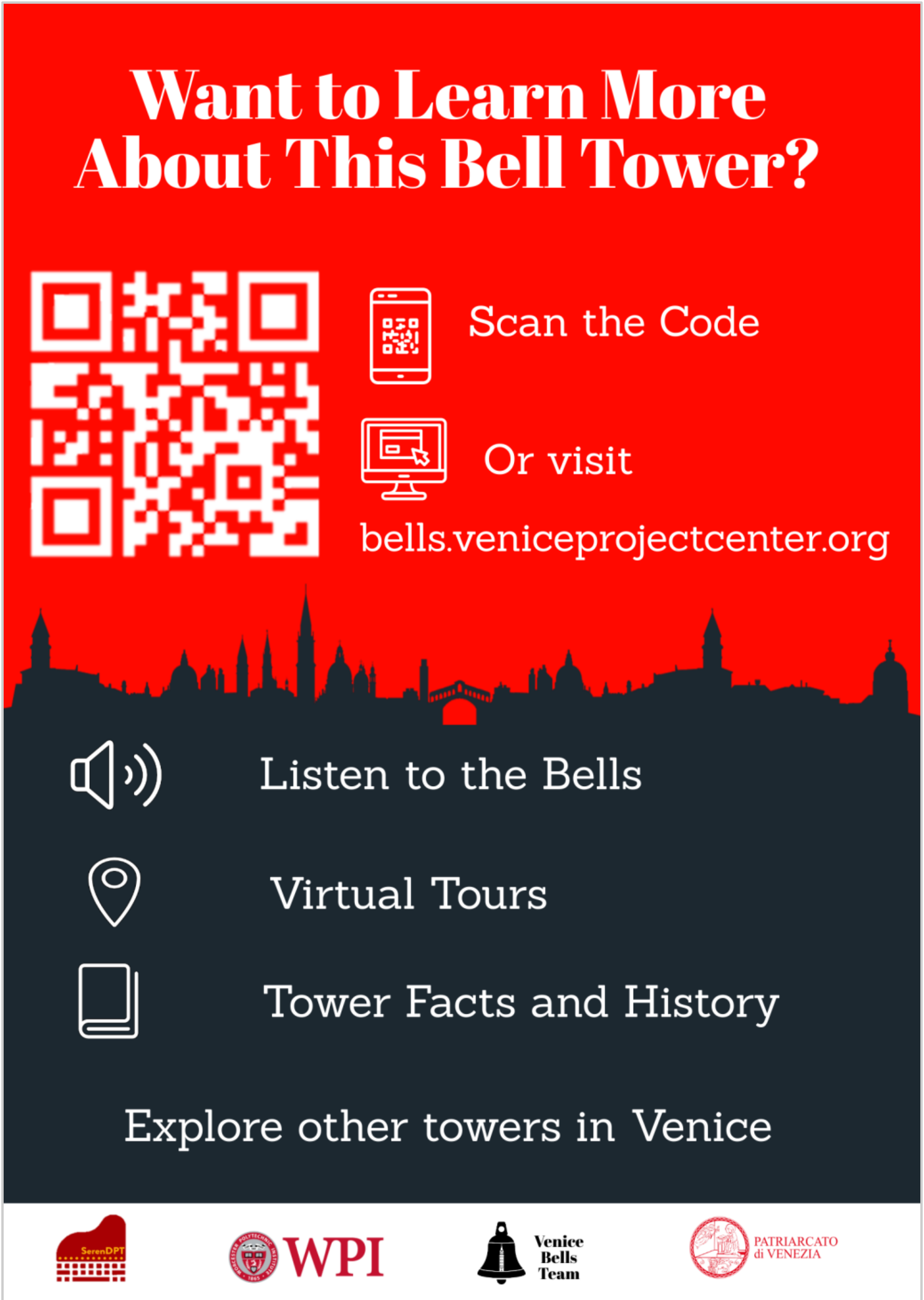

Figure 4.21: QR Code Flyer

The 3D model of the San Geremia bell tower is a sample of a way that churches could try to draw attention to donation bins. The model (23cm x 7cm x 7cm) is hollow to hold coins, and there is a slot at the roof designed to accept the diameter and thickness of any Euro coin (Figure

4.22). We also modeled a bottom opening in order to both secure the coins collected and allow retrieval of coins from the tower once it has reached its capacity (Figure 4.22). While the VPC did not have a 3D printer by the end of our project, the files of the 3D model have been submitted so that the VPC or SerenDPT can print the model once the VPC acquires a 3D printer.

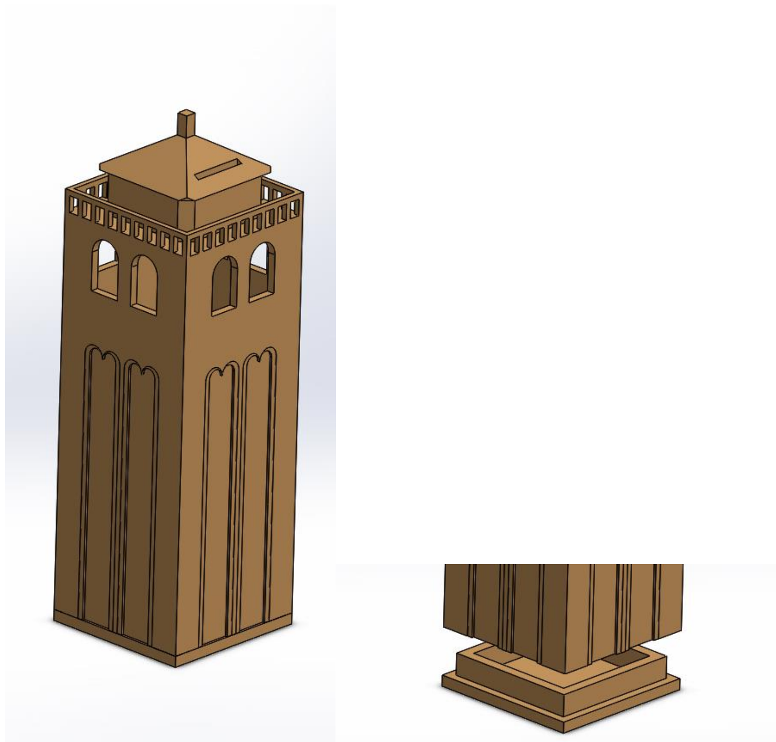

Figure 4.22: 3D Model of San Geremia with Bottom Opening

5. Conclusions and Recommendations

Over the course of 7 weeks we feel that we have contributed greatly to the efforts of the Venice Project Center, SerenDPT, and the Curia Patriarcale to document, improve the presentation of Venice's bells and promote the preservation of cultural heritage in the city of Venice. We were able to visit 11 towers, fully documenting 9 of those towers and 38 bells according to methods outlined by past projects. Furthermore, we developed methods to alert people to the state of Venice's bells and bell towers, as well as expanded on the VPC's interactive presentation of the data it has collected since the first bells and bell towers project in 1992. In addition, we have studied the dynamic behavior of the Bell Tower of Chiesa di San Salvador, drew conclusions on how bell swinging may affect the structural integrity of this church and worked on a plan for exploring realistic solutions that may reduce the high levels of accelerations in order to preserve the integrity of Venice bell towers. In addition to these substantive deliverables, we have recommendations that we believe will help our sponsors to preserve bells and bell towers in the future, as well as guide future projects in this area.

5.1 Recommendations for Future Projects

After working closely with the VPC's data storage infrastructure and observing the culmination of 10 bell tower research projects, we have a good understanding of the VPC's process of collecting and storing bell and bell tower data. We believe that after 7 weeks our understanding is more than sufficient for suggesting how the VPC's methods could be improved.

5.1.1 The Current State and Future of the Bells Project

Over the years that the Venice Project Center has been conducting this project, a lot of work has been put into collecting and organizing data from the bell towers, however this is not currently reflected in the database. Based on the previous teams' papers, we had concluded that 58 bell towers had been documented, however the database does not contain that much data. Every field in the database has a different number of towers that actually have data for that field. Based off of a brief analysis of the data in the database, we estimate that approximately 30-40 out of the 100 bell towers in the database have had their interiors documented, depending on how many fields need to have data in order to consider a tower sufficiently documented. Most of the database fields have data in 15-20 towers, but there are several key fields, such as belfry landing material, internal landing material, number of steps, frame type, and frame material that have data for 30-40 towers. These data in some cases could be missing because they are not applicable. For example, if there are no landings in a bell tower besides the belfry, it does not make sense to record an internal landing material. However, due to the inconsistency in the data, it is not possible to determine when the data has been collected as an empty field and when the data was just forgotten or not collected yet. In addition, the database is entirely missing many of the data fields that teams have collected. A list of the fields that are entirely missing from the database can be found in Appendix F. Furthermore, there are many fields that have duplicate fields that have typos or different spellings in their names, and the data may be spread out across these fields, making it difficult to identify how many towers contain this information. For example, all of the following are fields that exist in every tower in the database, with varying amounts of information in each field: " Number of ties and bands_Back" (notice the space at the beginning of the field name), "Number of ties and bands_Back" (with no space at the beginning), "Number of ties and bands _Back" (notice the space between "bands" and "_Back"), and "Number of ties bands_Back" (with no space). Finally, the data collected by the 2016 team is not in the database at all. A full account of what data has been documented for which towers can be found in a spreadsheet in our Google Drive named Data-Completeness.csv.

On top of these issues, the bells are stored in a separate group from the towers, but there is no reference to the bell database members within the tower members, nor is there a reference to the towers within the bells. As a result, the only way to identify the bells associated with a certain tower is to retrieve all of the bell data from the database and iterate through it looking for bells that have the same church name as the tower. If the church name in the bell members is at all different that the church name in the tower member, due to typos or inconsistent documentation, there is no way to link the two together. In addition, 3D models, audio recordings, and links to the bells' Venipedia pages are stored, not in the bell members, but in the towers.

If this project is to continue, we believe it is imperative that the data are better organized and that the gaps in the data gets identified. The first step to doing this is to overhaul the database. First, we believe that the database should be a relational database that allows for the use of SQL to interact with the data. This would allow for better access to and control over the data by the Bells web app and would allow for increased efficiency. The way the database currently works is that each member is a member of a specific group and is assigned a semi-random number as a unique identifier called a CKID. The only ways to get data out of the database are to retrieve an entire group and iterate through it looking for the data that you need or to know the semi-random CKID of the specific member that you want to to retrieve that directly. If the database could be interacted with through SQL, the web app could make queries to the database that could select and retrieve all members that match a set of criteria specified in the query, allowing the web app to directly retrieve exactly the data that it needs. This process is much more efficient than retrieving all data and searching for the specific data point desired.

Next, the design of the database should be manually created from scratch. Many of the field names in the current database are unclear due to being taken directly from a multi-sheet spreadsheet without thought to if the name still made sense without the separation of the sheets. An example of this is "Number of ties and bands_Back," which is present in both the Interior and Exterior sheets of the spreadsheet, but only present once in the database without any identifier as to which sheet it refers to. All of the fields should be named by hand in a descriptive way, or at least with external documentation as to what data they should hold. All of the duplicate and misspelled fields should be removed, and all of the missing fields should be added. Naming conventions should be standardized, so that there aren't discrepancies like one field being formatted like "Church name," while another is formatted like "Photos_Link." This would significantly aid in the ease of use of the database. There also needs to be a simple and consistent way of storing photographs in the database. As it currently stands, photos are stored as either CKIDs or filenames. In the case of filenames, the way to access the photos is to search a separate database group for the member with a matching filename and then get its CKID, then to handle it as if the CKID was just stored directly. In order to get a photo by CKID, the CKID needs to be inserted into the url https://s3.amazonaws.com/cityknowledge/testimages/{CKID}-original.jpg. This url can be used to access the image. Sometimes the url needs to be modified so that it ends with .JPG, but there is no indicator as to when this is necessary. Also, sometimes the picture is not available at either URL. Finally, there needs to be a simple way to programmatically input data into the database without using a web GUI like CKInput, which is difficult to use, or manually inputting the data into the CKData2 console.

Once the database has been overhauled, the data needs to be entered into the new database. For as much as possible, we recommend taking the data directly from the spreadsheets that each team has created, instead of taking it from the old database, as the spreadsheets are much more complete and better organized. This will also include the 2016 data, as well as the missing fields. After all the data is stored in the new database, it can be used to identify what towers have been documented and to what extent, and what gaps are remaining. We recommend using the bells as an indication that a tower has been documented. In the current database, there are 144 bells documented across 33 towers, with 172 bells across 40 towers if our data is included. However, while we have entered our data into the database, we have not been able to access the data from our bells due to a flaw in the City Knowledge console. By this standard, the towers that we consider to have been documented are listed in Appendix G. However, we strongly recommend that a future team re-examine the data more thoroughly to better determine what remains undocumented.

5.1.2 Recommendations

One of the difficulties that we encountered during this project was the the spreadsheets that we were initially using for data collection and storage were not descriptive or clear in what the fields meant or what data was stored where. In addition, since the methodology and data collected had been modified multiple times in the past few projects, we were unsure of exactly how to go about documenting the bells since we aimed to remain as consistent as possible with the past projects. In light of these issues, we believe it would be extremely worthwhile for the next bells and bell towers project to develop a final, standardized methodology for what should be documented and stored in the database. It is our hope that our updated data collection templates and glossary of bell tower data fields will be a stepping stone for a future project to further standardize the data collection process.

Furthermore, while we strived to deliver the best version of the Venice Bells Web App that we could in 7 weeks, we recognize that like any initial software release, it has some shortcomings. In particular, there were several features that we initially planned to include in the application that we ultimately decided would not be feasible to add in the time we had to make the app. For example, we initially wanted to include a donation link for bell towers to allow users to support maintenance and upkeep of the bells and bell towers; however, we quickly realized that the infrastructure to support this kind of system needs to be built first. We hope that if a future project is able to work with the Curia Patriarcale to establish a business model for actually restoring bell towers, they will also be able to add this feature to the Bells App to further help with funding. Moreover, we also discussed the possibility of allowing users to get directions to a specific bell tower from anywhere in Venice. Once we began building the app and explored this feature further, we realized it would have taken far more time than we initially expected and that we would not be able to complete it in time. Nonetheless, because Leaflet is an open-source library, there are open-source plugins and extensions designed specifically for use with Leaflet which can be used for routing applications.

5.2 Reflections on Structural Integrity Experiment

After 7 weeks of refining our methods to best assess the structural integrity of the bell tower of San Salvador, we have learned a great deal about the strengths of our study. We believe we have developed a solid methodology for measuring the interaction between bell swinging forces and the natural frequencies of a bell tower. However, due to limitations we were not able to draw the conclusions on the safety of the San Salvador bell tower that we originally sought. Nonetheless, we believe there is promise in this methodology and have ideas for how it could be refined by future projects.

5.2.1 Conclusions on Methodology

The development of our methodology in this experiment was overall a success. Firstly, we were able to develop a sound process for determining the natural frequency of a bell tower. While the structural modeling technique has to be made custom for each bell tower, the process that we have outlined will allow future projects to easily create these models for any bell tower that they have accurate geometric data for. The ability to calculate the natural frequencies of bell towers is useful not only for observing the effects of bell swinging, but for observing the tower's response to any dynamic force such as earthquakes or wind. Additionally, we were able to collect vibrational patterns in the bell tower using low-cost, easily accessible accelerometers. Of particular note is that we were able to conveniently use an Android phone for measurements, which appeared to be sufficient in its precision and noise floor. Finally, with our methods we were able to develop a way to extract meaning from the data we collected. We showed that we could indeed extract the lower harmonics of the horizontal forces caused by bell swinging using fast Fourier analysis in MATLAB. These three points lead us to believe that our methodology is at the least a good starting point for further research on the topic of structural integrity of Venice's bell towers.

Nonetheless, while we are confident in our methods, we are not yet certain that a definite conclusion can be made on the safety of bell swinging in the bell tower of San Salvador. In our results, we found that the third horizontal harmonic was within 20% of the first and second natural frequencies of the tower, which seemingly indicates at least a minor problem with the bell swinging methods in the bell tower of San Salvador. However, DIN4178 does not provide a standardized methodology with which to compare ours to determine if we can make judgements based on the standard. Our results compare well with other studies that have tested against DIN4178 standards, but the lack of a standardized methodology to compare to is still cause for skepticism. In addition, we feel that due to time restraints and complications with logistics, we were not able to measure a large enough quantity of data for us to be confident in the results. Similarly, due to the time constraints we were not able to perform as detailed analysis on the entire waveform as we would have liked, leaving some doubt in our mind about the meaningfulness of the analysis. Likewise, the overall good condition of the San Salvador bell tower in comparison to the towers we surveyed as part of our data collection, is an indication that the bell swinging is not severely hazardous. Given these points, we cannot make a definite conclusion on the safety of bells swinging in San Salvador.

5.2.2 Shortcomings and Future Implications

While we feel that we have developed a good methodology that can be expanded upon in the future, we also recognize that there were some flaws and shortcomings in our experiment as a whole. For example, we noticed in our research that many past studies used piezoelectric accelerometers rather than the MEMS accelerometers we used. Many studies also used uniaxial accelerometers rather than triaxial to isolate the individual force components during measurement. Furthermore, we were severely limited in our data collection capabilities due to logistical issues. We were only able to schedule visits to the tower on two days, and therefore only have four measurements: two from the belfry on each day. In order to be sufficiently confident with our measurements and analysis, we would need to collect many more measurements in different parts of the bell tower (for example, the belfry walls). Finally, because of the limited data collection and how late in the project it was performed (November 26, 2 weeks before our final presentation), we did not get to perform as in-depth of an analysis as we had hoped. The acceleration waveform was very dynamic and yielded very different frequency results depending on where in time the Fourier analysis was performed. If we had more time to analyze the data, we would have tried to make generalizations among the whole waveform, not just the period where the bells were swinging with maximum force. While we believe our dataset is an accurate measurement, we would require a larger sample in order to be sufficiently confident.

In light of the shortcomings and flaws mentioned above, we have recommendations for future teams to improve on our work. With regard to the accelerometers, we feel that it might be worthwhile to re-apply this methodology using uniaxial, piezoelectric accelerometers. It was unclear from our research what their advantages may be over triaxial, MEMS accelerometers like we used, but we feel that it is at least worth exploring. Additionally, we highly recommend that if a future project continues with this work that they should determine as early as possible which bell tower(s) they will study, and that they make arrangements for multiple days of measurement well in advance. It was very late in our project by the time we were able to actually collect our data, and it would have been greatly beneficial to us to have had more time to collect and analyze the data. More time will allow for both the collection of a larger dataset and more in-depth data analysis, and we would recommend that the next project investigate ways to analyze the entirety of the waveform. In short, despite the shortcomings of our initial experiment, we consider it worthwhile to explore our methodology further based on these recommendations. We certainly hope that future projects may continue our work in order to have a significant impact in assessing the safety of Venice’s bell towers.

5.3 Suggestions for Preserving Bell Towers

Our data collection and photographs have gone towards the preservation of the tower in documentation. This allows for the tower to have a historic record and reference for the tower to be rebuilt if it ever falls like San Marco did. There are many ways that we can physically preserve the bell towers as well. Through our visits we saw methods like ties and bands and other forms of restoration such as staircase or brick replacement.

To help in the preservation of Sant'Andrea we suggest that there be a major cleanup of the tower. This was by far the worst tower in terms of cleanliness and should have not reached that condition. After the cleanup the bird nets would need to be replaced and any holes in the roof would need to be patched. The stairs and structure of the tower were very sound and are not in need of repair.

Figure 5.1: Unclean Conditions in Sant'Andrea Belfry

San Polo was overall in very good condition, however it's top landing and flight of stairs to the belfry was in very bad shape. The landing had cracks and holes making it unstable and on the stairs we leaned against the tower wall to ascend to the belfry. Strangely, the bottom of the tower had newly replaced stairs, yet, the top flight had not been repaired. With these repairs and the addition of artificial lighting, the tower would be one of the best preserved towers in Venice and possibly become a tower for visitation.

Figure 5.2: Hole in Top Landing of San Polo

San Geremia had one of the worst staircases we experienced throughout our visits. It would require extensive repair and time to replace the entire staircase. The tower had also some structural issues with its walls. These issues would require further study to see if they were detrimental to the tower's health and would require extensive repair. In the meantime, we could suggest more temportray repairs suchs as ties or bands to hold the tower in place and extend its lifespan.

Sant'Eufemia being a smaller tower, does not need as much work as some of the larger ones. The tower structure was in good shape with only its interior in need of repair. The stairs leading to the first landing were missing and would need replacement. Also the top landing was very unstable and would require replacement as well.

Figure 5.3: Staircase of Sant'Eufemia

San Benedetto was overall in very good condition. However, the bells of the tower were very bad and need attention. This would require a campanologist to come and inspect the bells' sides and clappers. The frame was also in very bad shape and would need to be replaced at some point.

The tower repairs and restoration were not the direct focus of our project and therefore all we can offer are suggestions that we felt are important. We recommend that future teams look into the possibility of creating a business model to help employ Venetians to work on the towers, keeping jobs within the city. For example, in the context of such project one could possibly decide which repairs should be made, prioritize them and calculate how much it would cost to implement these repairs and then one could look into the feasibility of creating a business for the repair and maintenance of Venetian bells and towers.

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Appendix A -- Tower Data Fields

Table A.1: General Tower Data Fields

General	
Church_Name	Text Name of Church
Tower_Code	Text 4-letter tower code (i.e. OGNI)
Date_Visited	Date Date of this visit
Proprietor	Text Owner of church (typically Curia Patriarcale)
Paster Name	Text Name of current pastor
Danger_Zone	Text List of buildings contained in potential fall zone School, church, campo, residential area, shopping area
Significant_history	Text History of the church, bell tower, and bells; churchesofvenice.co.uk is a good source for when the pastors are not very helpful
Construction_year	Number Year the tower was built
Repair_year	Number Year the tower was repaired/rebuilt
Repair_description	Text Description of tower repairs
Renovation_Restoration_years	Number Year of restoration or renovation
Renovation_Restoration_description	Text Description of tower restoration/renovation
Architecture	Text Style of architecture
Type	Standard (S), Roman (R), Vela (V), Other (O)
Architect	Text Name of architect
Location	

Longitude	Number Global latitude and longitude (use decimals, not DMS)
Latitude	
Sestiere	Text Sestiere of church/tower
Time_open_1	Time Times of day the church is open (if known)
Time_open_2	
Fire Protection	
Distance_From_Canal	Number Distance in m to nearest canal
Number_Water_Sources	Number Number of nearby water sources (canals, fountains, etc)

Table A.2: Tower Exterior Data Fields

Exterior_General	
Type	Standard (S), Roman (R), Vela (V), Other (O)
Number_of_Bells	Number Number of bells
Bell_Tower_Parts	
Picture_Drive	
Tower_Height_m	Number Height of tower in meters
Material	Text Dominant material of tower
Exterior_Block_Height_cm	Number Height of exterior bricks
Exterior_Block_Width_cm	Number Width of exterior bricks
Exterior_Block_Depth_cm	Number Depth of exterior bricks; will likely need to be measured at a corner
Orientation and Inclination of Tower	
Orientation_degrees_Front	Number Compass degrees, with front of phone pointed towards the tower walls
Orientation_degrees_Right	
Orientation_degrees_Back	
Orientation_degrees_Left	
Inclination_rating	0 (none), 1 (slight), 2 (serious)
Inclination_direction	FBLR
Inclination_calculated	Number Degrees of inclination; measured with a smartphone level to estimate
Public Access, Accessibility, and Doors	
Public_access	Boolean Can the general public access the tower

Accessibility_Front Accessibility_Right Accessibility_Back Accessibility_Left	Boolean Is the tower accessible from each side
How to Access Tower	Text Brief description of how to enter bell tower
Exterior_Door_Front Exterior_Door_Right Exterior_Door_Back Exterior_Door_Left	Boolean Is there a door on the exterior tower on each side
Exterior_Door_Height_cm Exterior_Door_Width_cm	Number Dimensions of exterior door in cm

Visibility of Tower	
Public Visibility	
Visibility_Front Visibility_Right Visibility_Back Visibility_Left	Number Percentage of each side of tower that is visible from the outside
Visibility_Distance_Front Visibility_Distance_Right Visibility_Distance_Back Visibility_Distance_Left	Number Distance the above estimate was observed from
Notes	
Exterior_Tower_Notes_Front Exterior_Tower_Notes_Right	Text Any important notes on each side of tower

Exterior_Tower_Notes_Back	
Exterior_Tower_Notes_Left	
Building Connections	
Connected_to_Front	Text What nearby buildings (if any) each side of the tower is attached to.
Connected_to_Right	
Connected_to_Back	
Connected_to_Left	
Length_attached_percentage_Front	Number Percentage of each side that is attached to said structure
Length_attached_percentage_Right	
Length_attached_percentage_Back	
Length_attached_percentage_Left	
Decorations Outside	
Num_Plants_Front	Rating Quantity of plants 0 (none) to 4 (countless)
Num_Plants_Right	
Num_Plants_Back	
Num_Plants_Left	
Num_art_pieces_Front	Number Number of art pieces on each side
Num_art_pieces_Right	
Num_art_pieces_Back	
Num_art_pieces_Left	
Num_Exterior_Inscriptions	Number Number of inscriptions on exterior
Inscription	Text The actual text of the inscription
Avg_inscription_legability	Rating Legibility of inscription 0 (best) to 4 (worst)

Num_decorations	Number Number of decorations on the exterior
Decoration_description	Text Textual description of decorations
Decoration_condition	Rating Overall condition of decoration 0 (best) to 4 (worst)
Tower Defects	
Num_cracks_holes_Front	Rating 0 (none) to 4 (countless)
Num_cracks_holes_Right	
Num_cracks_holes_Back	
Num_cracks_holes_Left	
Num_brick_colors_Front	Number Number of different colors of brick
Num_brick_colors_Right	
Num_brick_colors_Back	
Num_brick_colors_Left	
Num_ties_bands_Front	Number Number of metal fastenings in the brick used to hold tower together
Num_ties_bands_Right	
Num_ties_bands_Back	
Num_ties_bands_Left	
Restoration	
Restoration_Visible_Front	Boolean Are there any visible restoration efforts, such as a large section of different colored brick?
Restoration_Visible_Right	
Restoration_Visible_Back	
Restoration_Visible_Left	

Clock	
Clock_Present	Boolean Presence of a clock
Clock_Working	Boolean Whether or not the clock works
Clock_Mechanism_Landing	Number The landing number the clockwork is placed on
Belfry/Roof Specific Data	
Number_lesene	Number A lesene is a narrow vertical pillar in a wall, like a pilaster
Number_sections	Number Number of sections belfry is divided into
Arches_Front	Number Number of arches on each side of belfry
Arches_Right	
Arches_Back	
Arches_Left	
Belfry_style	Text
Drum_type	Text Shape of drum above belfry
Balustrade	Boolean Existence of these elements
Attic	
Cross	
Weathervane	
Lightning_rod	
Lightning_rod_grounded	Text (Yes, No, Unclear) Does the lightning rod have a grounding wire
Finial	Boolean Existence of a finial
Finial_type	Text
Finial_description	Text Description of finial

Table A.3: Tower Interior Data Fields

General	
Door_Side	FBLR Side of tower the entrance is on
Door_Height_cm	Number Height of entrance door in cm
Door_Width_cm	Number Width of entrance door in cm
Num_Landings	Number Number of floors in the tower (ground and belfry included)
Clock_Mechanism_Landing	Number Number of the landing the clock mechanism is if applicable

Basic Landing Info	<--- Add more landings if necessary
Landing_Material	Text Wood, Brick, Stone, Concrete, Marble, Tile, Other
Landing_Sturdiness	Rating 0 (best) to 4 (worst) Sturdiness of Landing
Landing_Cleanliness	Rating 0 (best) to 4 (worst) Overall cleanliness of landing
Landing_Length_cm	Number Length of landing in cm (Front to Back)
Landing_Width_cm	Number Width of landing in cm (Left to Right)
Landing_Height_cm	Number Landing height in cm (floor to ceiling)
Natural_Lighting	Rating 0 (best) to 4 (nonexistent)
Artificial_Lighting	Rating 0 (best) to 4 (nonexistent)
Notes	Text

Stairs Info	****** Note that all references to stairs and ramps refer to those used to climb upwards to the NEXT landing ******
Ramp_presence	Boolean Presence of ramp to next landing

Stairs_presence	Boolean Presence of stairs to next landing
Staircase_Side	FBLR Side of tower the staircase is on
Stair Height	Number Average heigh of steps in cm
Staircase_Material	Wood, Brick, Stone, Concrete, Marble, Tile, Other
Number_of_Steps to next landing	Number Number of steps in staircase
Num_Bad_Steps	Number Number of broken/unsturdy stairs
Staircase_Cleanliness	Rating 0 (best) to 4 (worst)
Staircase_Sturdiness	Rating 0 (best) to 4 (worst)
Railing sturdiness	Rating 0 (best) to 4 (no railing)
Notes	Text Any important additional info

Wall Thickness and Windows	
Block_Height_cm	Number Height of bricks
Block_Width_cm	Number Width of bricks
Block_Depth_cm	Number Depth of bricks; likely needs to be measured at a window
Wall_Material	Text Brick, Stone, Cement, Plaster, Brick/Plaster
Wall_Thickness	Number Thickness of walls in cm; must be estimated at a window
Num_Windows_Front	Number Number of windows on each side
Num_Windows_Right	
Num_Windows_Back	
Num_Windows_Left	

Window_Height_cm	Number Height of windows in cm
Window_Width_cm	Numer Width of windows in cm
Window_Depth_cm	Number Depth of windows in cm; typically the same as wall thickness

Interior Doors	
Interior_Door_Front	Boolean Presence of door on each side
Interior_Door_Right	
Interior_Door_Back	
Interior_Door_Left	
Interior_Door_Height_cm	Number Dimensions of door in cm
Interior_Door_Width_cm	
Interior_Door_Depth_cm	
Interior_Door_Notes	Text Any notable information about the door

Restoration	
Restoration_Sides	FBLR Visible restoration efforts on a given side
Number_of_Ties_and_Bands_Front	Number Number of metal fastenings in the brick used to hold tower together
Number_of_Ties_and_Bands_Right	
Number_of_ties_and_Bands_Back	
Number_of_Ties_and_Bands_Left	

Tower Defects	
Number_Cracks_and_Holes_Front	Rating 0 (none) to 4 (countless)
Number_Cracks_and_Holes_Right	
Number_Cracks_and_Holes_Back	

Number_Cracks_and_Holes_Left	
Length_of_Cracks_and_Holes_Front	Rating 0 (negligible) to 4 (extreme damage)
Length_of_Cracks_and_Holes_Right	
Length_of_Cracks_and_Holes_Back	
Length_of_Cracks_and_Holes_Left	
Number_Damage_Stone_Front	Rating 0 (none) to 4 (extreme damage)
Number_Damage_Stone_Right	
Number_Damage_Stone_Back	
Number_Damage_Stone_Left	
Number_Misaligned_Brick_Front	Rating 0 (none) to 4 (countless)
Number_Misaligned_Brick_Right	
Number_Misaligned_Brick_Back	
Number_Misaligned_Brick_Left	

Belfry Only	
Frame_Type	A-Frame (A), H-Frame (H), or Other (O)
Frame_Restoration	Boolean Has the frame been restored?
Frame_Material	Wood (W), Metal (M), Other (O)
Frame_missing_screws_bolts	Rating 0 (none) to 4 (countless)
Frame_rust	Rating 0 (none) to 4 (extreme)
Frame_cracks	Rating 0 (none) to 4 (extreme)
Frame_cleanliness	Rating 0 (very good) to 4 (poor)
Frame_warping	Rating 0 (none) to 4 (extreme)
Number_of_Frame_dents	Rating 0 (none) to 4 (countless)

Frame_Overall_condition	Rating 0 (very good) to 4 (very poor)
Belfry_Opening_Side	FBLR Side of the entrance to the belfry
Belfry Width	Number Width of belfry in cm (L to R)
Belfry Length	Number Length of belfry in cm (F to B)
Condition inside roof	Rating 0 (very good) to 4 (very poor)
Bird_Net_Condition	Rating 0 (very good) to 4 (nonexistent)
Drain_Holes_Condition	Rating 0 (very good) to 4 (nonexistent)
Closest_Bell_Tower	Text Nearest bell tower
Frame_Notes	Text Additional info on frame

Decorations and Inscriptions	
Num_internal_inscriptions	Number Number of text inscriptions
Internal_transcription	Text Transcription of each inscription
Num_internal_decorations	Number Number of internal engravings
Internal_decoration_locations	FBLR
Internal_decoration_description	Text Description of each engraving
Internal_average_legibility	Rating 0 (perfectly legible) to 4 (entirely illegible)
internal_average_conservation	Rating 0 (Very good) to 4 (Very poor)

Table A.4: Bell Data Fields

Note and Ringing Times	
Musical_Note	Text Musical note when rung
Frequency_Hz	Number Frequency in Hz when rung
Chiming_frequency	Never (N), Hourly (H), Half-Hourly (HH), Quarter-Hourly (QH), Other (O), Unknown (U)
Ringing_Times_Monday	Times of day when rung
Ringing_Times_Tuesday	
Ringing_Times_Wednesday	
Ringing_Times_Thursday	
Ringing_Times_Friday	
Ringing_Times_Saturday	
Ringing_Times_Sunday	
Engravings and Inscriptions	
Crown_Engraving_Front	Text Descriptions of engravings on crown
Crown_Engraving_Right	
Crown_Engraving_Back	
Crown_Engraving_Left	
Body_Engraving_Front	Text Descriptions of engravings on body
Body_Engraving_Right	
Body_Engraving_Back	
Body_Engraving_Left	
Lip_Engraving_Front	Text Descriptions of engravings on lip
Lip_Engraving_Right	

Lip_Engraving_Back	
Lip_Engraving_Left	
Crown_Inscription_Front	Text Inscriptions on the crown Format: INSCRIPTION TEXT ["illegible" if can't be read]
Crown_Inscription_Right	
Crown_Inscription_Back	
Crown_Inscription_Left	
Body_Inscription_Front	Text Inscriptions on body
Body_Inscription_Right	
Body_Inscription_Back	
Body_Inscription_Left	
Lip_Inscription_Front	Text Inscriptions on the lip
Lip_Inscription_Right	
Lip_Inscription_Back	
Lip_Inscription_Left	
Number_of_Decorations	Number Number of engravings
Number_of_Inscriptions	Number Number of inscriptions
Clapper and Stock	
Clapper_Present	Boolean Is there a clapper?
Clapper_Rust	Rating 0 (none) to 4 (completely rusted)
Clapper_Condition	Rating 0 (very good) to 4 (very poor)
Clapper_Length_cm	Number Length of clapper in cm
Belt_Material	Text Material of belt

Stock_Material	Text Material of stock, typically metal or wood
Skidmark_1_Side	FBLR Side of the bell the first skidmark is on
Skidmark_1_cm	Number Length of skidmark 1 in cm
Skidmark_2_Side	FBLR Side of the bell the second skidmark is on
Skidmark_2_Right_cm	Number Length of skidmark 2 in cm
Conservation_state	Rating 0 (Very Good) to 4 (Very Poor)
Safety_cable	Boolean Presence of a safety cable
Ringing Method and Info	
Ringing_method	Hammer (H) or Wheel (W)
Swing_direction	FBLR-FBLR
Hammer_side	FBLR Side the hammer is on (if any)
Reason_not_rung	Text Description of why the bell isn't rung (if applicable)
Automatic_ringing	Boolean Automatic ringing mechanism?
Manual_ringing	Boolean Manual ringing mechanism?
Historic Information	
First_casting	Number Year of first casting
Second_casting	Number Year of second casting
Historic_info.	Text Any significant history that can be determined
Foundry	Text Name of founder/foundry

Place_of_Casting	Text Location of founding
Physical Properties	
Thickness_mm	Number Thickness in mm measured at the thickest part of lip
diameter_cm	Number Diameter across mouth
height_internal_cm	Number Internal height in cm from lip to crown
height_ground_cm	Number Height to lip in cm from ground
Cracked_Sides	FBLR, None Side of the bell that is cracked
Cleanliness_Rating	Rating 0 (Very Good) to 4 (Very Poor)
Discoloration_Rating	Rating 0 (None) to 4 (Entirely discolored)
Chips_Rating	Rating 0 (None) to 4 (Countless)
Decoration_Legibility	Rating 0 (Perfectly clear) to 4 (entirely illegible)
Overall_Condition	Rating 0 (best) to 4 (worst)

Appendix B -- Accessibility Criteria

Table B.1: Safety Criteria

Criteria	**Grade 1**	**Grade 2**	**Grade 3**	**Grade 4**	**Grade 5**
Roominess of Landing	Cluttered landings, no path between levels	Cluttered landings, but some path from level to level	Landings used for storage, but clear path for maneuvering	Clear landings and stairs/ramps	Clear, open, and spacious landings and stairs/ramps
Presence of Railings in Landings	No railings	Railings for stairs, but not for landings in shaft	All landings in shaft have railings, but they are unstable	All landings have railings in satisfactory condition	All landings have railings in great condition
Condition of Landings	Excessive holes in floor, difficult to navigate safely	Many holes in stairs and landings	A few unobstructive holes throughout landings	Little to no holes anywhere, no obstructions	No holes or obstructions anywhere
Sturdiness of Stairs/Ramps	Crumble under walking pressure	Many holes in wooden stairs/ramps	A few holes in wooden stairs/ramps	Satisfactory sturdiness of stairs and ramps	Stairs and ramps are very sturdy and very secure
Integrity of Walls	Frequent cracking throughout shaft and belfry	Few cracks in walls of shaft and belfry	Some interior bricks are crumbling	Bricks in satisfactory condition throughout tower	Bricks in great condition throughout tower
Window Netting	No netting anywhere	Some belfry windows have netting	Majority of belfry windows have netting	Majority of belfry and shaft windows have netting	All windows have netting or screens
Lighting in Shaft	No lighting, flashlight necessary	Broken lighting on each level	Lights on majority of landings work	Lighting works on every level of landing	Lighting present and working everywhere
Condition of Wood	Wood rot everywhere	Wooden stairs intact but unsturdy	Wooden stairs in satisfactory condition	Wooden stairs in good condition, satisfactory sturdiness	No wood rot anywhere, all stairs/landings in great condition

Belfry Maneuverability	Low hanging bells, safety concern	Bells are low hanging, safe but cannot be maneuvered around	Maneuvering around bells is manageable but difficult	Slight ducking under bells required	Bells do not interfere with maneuverability
Belfry Size	Only one person can fit in belfry	2-3 people can fit in belfry	4-5 people can fit rather uncomfortability	Spacious, 4-5 people can easily walk around	Spacious, a large group of people can maneuver easily
Belfry Ease of Entrance	Very small entrance, assistance needed to enter	Difficult to enter belfry, but manageable	Satisfactory ease of entrance	Entering belry is easy and safe but requires a little effort	Entering belfry is entirely safe and requires no extra effort

Table B.2: Cleanliness Criteria

Criteria	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5
Cleanliness of Walls	Graffiti on interior and exterior walls	Interior and exterior shaft walls are very dirty	Interior and exterior walls have some markings	Clean interior and exterior walls	Clean interior and exterior walls with evident upkeep
Bird Droppings on Bells	All bells are thickly covered	All bells are somewhat covered	Some of the bells are slightly covered	Little to no droppings on bells	No droppings on any bells
Bird Droppings in Towers	Inches of bird droppings everywhere	Frequent bird droppings throughout tower	Some droppings throughout tower	Little to no droppings throughout tower	No droppings anywhere in tower
Bird Infestation	Belfry covered with bird feathers and nests, constant bird activity	Bird feathers everywhere, some bird activity	Some bird feathers or nests, occasional bird activity	Little to no feathers or nests, no activity	No signs of birds at all
Animal Remains	Excessive amount of carcasses throughout tower	Some carcasses throughout tower	A few carcasses throughout tower	Little to no carcasses throughout tower	No carcasses at all throughout tower
Plant Presence	Plants growing all over the tower	Many plants growing in belfry and.or shaft	Plants growing in small sections of tower	Little to no plant growth	No plant growth at all

Appendix C - Data Analysis Criteria

From the master weight list in Appendix D the following fields were used to calculate Bell rankings:

Conservation_state
Cracked_side
Cleanliness
Discoloration
Overall_condition
Chips Rating

From the master weight list in Appendix D the following fields were used to calculate Belfry rankings:

Landing_Cleanliness
Frame_cleanliness
Frame_warping
Frame_Overall_condition
Condition_of_inside_of_roof
Drain Holes Rating
Bird_net_condition

From the master weight list n Appendix D the following fields were used to calculate Landing rankings:

Landing_Sturdiness
Landing_Cleanliness
Natural_Lighting
Artificial_Lighting
Staircase_Cleanliness
Staircase_Sturdiness
Railing_Sturdiness

Appendix D - Criteria Weights

The following is a list of all the fields we used to rank towers. The list is structured as follows (Field : Weight). Field is the database entry, and Weight is the value that multiplies the calculated value of the corresponding that field for rankings.

Landing_Sturdiness : 2
Landing_Cleanliness : 1
Natural_Lighting : 0.4
Artificial_Lighting : 0.1
Staircase_Cleanliness : 1
Staircase_Sturdiness : 2
Railing_Sturdiness : 2
Frame_cleanliness : 1
Frame_warping : 0.1
Frame_Overall_condition : 2
Condition_of_inside_of_roof : 0.5
Drain Holes Rating : 1
Railing : 2
Bird_net_condition_front : 2
Calculated_vibration : 1
Conservation_state : 1
Cracked_side : 2
Cleanliness : 1
Discoloration : 0.2
Overall_condition : 2
Clapper_condition : 0.5
Belt_condition : 0.5

Inclination_rating : 1
Cracks:1
Plant Growth: 0.25
Misaligned Bricks: 0.25

Appendix E - Process of Ranked Towers

The fields we used to rank towers is listed in Appendix D. With these fields we used the following process to rank towers.

Step I: Convert Fields to Grade of 0 - 100
There were four fields of criteria recorded per tower, interior, exterior, bells and overall impression.

Interior, Exterior and Bells were ranked on a 0-4 scale and overall impression was ranked on a 0-5 scale. For the 0-4 scale the scores were multiplied by 25 to fit the 0-100 scale and for the 0-5 scale they were multiplied by 20. For boolean fields we assigned a 'yes' a value of 100 and a 'no' a value of 0. Frame material was the only field that was selection field. For this field we assigned 50 to metal and 100 for wood. If a field has no data it is given a value of 'x' which represents no record.

Step II: Aggregate The Average of Each Field That is Collected in Bells or Landings
The 0 - 100 value of fields that are collected for each Landing or Bell of the Belltower are averaged into one value out of 100. For example, if a bell tower with 3 landings and a belfry received a 4, 3, 2, 5 rating for Frame_cleanliness it would be converted to 80, 60, 40, 100 and averaged to 70. Thus making the rating for Frame_cleanliness for that belltower 70.

Step III: Multiply 0 - 100 Rating By Weights
Each 0 - 100 calculated rating is then multiplied by its field's respective weight which can be found in Appendix D. The resulting value is the weighted field rating.

Step IV: Calculated Tower Rating
All of the weighted field ratings of the bell tower are summed up. If a field was given an 'NR' in step I it is ignored. The tower's sum is then divided by the sum of the weights of the fields that were used (the weight of the fields that were not assigned a value of 'NR').

Step V: Rank Towers
Once an overall rating ranked with all of the other towers who have received a total tower condition rating.To calculate the rankings of Interior, Exterior, Bells and Belfry you follow the same steps of the overall
rating but only with the fields that correspond to that section. These corresponding fields can be found in Appendix C.

Appendix F -- Fields Missing from Database

Exterior

- Visibility Front
- Visibility Left
- Visibility Back
- Visibility Right
- Visibility Distance Front
- Visibility Distance Left
- Visibility Distance Back
- Visibility Distance Right
- Connected to Front
- Connected to Left
- Connected to Back
- Connected to Right
- 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_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
- Belfry_style
- Drum_type
- Connected_wire
- Connected_unclear

Interior

- Landing Sturdiness
- Landing Cleanliness
- Landing Length F-B (cm)
- Landing Width R-L (cm)
- Staircase Cleanliness
- Staircase Sturdiness
- Railing

- Block Height (cm)
- Block Width (cm)
- Block Depth (cm)
- Window Side
- Window Height (cm)
- Window Width (cm)
- Window Depth (cm)
- 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
- Frame rust
- Frame cracks
- Frame cleanliness
- Frame warping
- Frame dents
- Frame Overall_condition

Appendix G -- Documented Towers

- Bell Tower of Santa Maria Assunta di Torcello
- Bell Tower of Basilica di San Marco
- Bell Tower of Santa Maria dei Miracoli
- Bell Tower of San Giorgio Maggiore in Isola
- Bell Tower of San Canciano
- Bell Tower of Santa Eufemia
- Bell Tower of Santa Maria Assunta dei Gesuiti
- Bell Tower of San Benedetto
- Bell Tower of San Bartolomeo
- Bell Tower of San Silvestro
- Bell Tower of San Michele
- Bell Tower of Ognissanti
- Bell Tower of San Giacomo dell'Orio
- Bell Tower of Sant'Eustachio
- Bell Tower of San Nicolo dei Mendicoli
- Bell Tower of San Marciliano
- Bell Tower of Santa Maria Gloriosa dei Frari
- Bell Tower of San Geremia e Lucia
- Bell Tower of S. Cristoforo
- Bell Tower of San Giobbe e Barnardino
- Bell Tower of San Martino di Castello
- Bell Tower of Santa Sophia
- Bell Tower of Santa Maria Mater Domini
- Bell Tower of Malamocco
- Bell Tower of San Francesco de la Vigna
- Bell Tower of S. Felice
- Bell Tower of Santa Maria Formosa
- Bell Tower of S. Alvise
- Bell Tower of Santissimo Redentore
- Bell Tower of San Cassiano

- Bell Tower of Santa Fosca
- Bell Tower of S. Maria e Donati
- Bell Tower of Santa Maria di Nazareth
- Bell Tower of S. Apostoli
- Bell Tower of S. Elena
- Bell Tower of Sant'Aponallinare
- Bell Tower of San Giovanni Grisostomo
- Bell Tower of Ss. Salvatore
- Bell Tower of Sant'Andrea della Zirada
- Bell Tower of San Polo