AN ABSTRACT OF THE THESIS OF

Morvarid Dilmaghani for the degree of Master of Science in Wood Science presented on September 6, 2019.

Title: Usefulness of Structural Health Monitoring for the Wood Construction Industry: Global and Local Perspectives

Abstract approved:

_____________________________________________________
Mariapaola Riggio

In recent years, multiple historic and contemporary timber buildings have been instrumented with sensors to monitor the performance of wood products and novel engineering systems. While literature states the potential of structural health monitoring (SHM) data to inform decision-making process of key stakeholders in the architects, engineers, contractors and manufacturers (AEC) industry, there is little evidence that the information embedded in SHM data is fully exploited. The objectives of this research are to better investigate the current use of SHM data by the wood construction industry to understand how the industry uses information from this data to make decisions. This research also aimed to understand which features of the currently available SHM platforms and data visualization tools were considered useful by AEC users for a range of different monitoring applications.

In order to achieve these objectives, this study included two main phases: 1) a literature review of timber SHM projects with the scope of identifying the main fields of application of SHM in timber buildings, the types of data produced and their use; 2) a survey among mass timber stakeholders in the U.S. Pacific Northwest to understand their perceptions on the value of SHM data, and preferences for ways to access and visualize monitoring data.
In the first phase, a systematic literature review was conducted by defining review scopes, literature search, practical screening, quality appraisal, data extraction, analysis of studies, and writing the review. This synthesis of the literature covers peer-reviewed research articles and grey literature investigating timber SHM projects. The literature survey focusing on projects examined in detail seventy-one (71) papers documenting monitoring of 193 timber structures from 1980 to 2019.

In the second phase, a web base survey was developed. The questionnaire included a total of 15 questions focused on three sections: 1) demographic information, perceptions on: 2) the applicability and usefulness of monitoring data, and 3) the accessibility and communication of monitoring data. The target population of this study was designers (architects, engineers), contractors and manufacturers in the U.S. Pacific Northwest mass timber industry. In this phase, forty responses were further analyzed. As a limitation of the method, partial responses were not possible to record, so an exact response rate could not be calculated.

Results of the literature review show that building owners mostly used SHM to assess structural safety/serviceability and damage of existing and historical buildings. The data-informed actions were mostly taken in buildings monitored for safety/serviceability assessment purposes. The results also show that most of the documented projects were research-driven. These projects reflect activities conducted by researchers. Research-driven projects provided useful information to evaluate a building performance and/or to validate/calibrate numerical models.

Results of the survey show that comparing designed with measured performance of a building was considered the most useful SHM application by the respondent group of wood construction stakeholders in the Pacific Northwest. Given the interest of academia and industry in similar applications of SHM data, interaction, between those who produce and analyze the data (mainly researchers) and decision-makers, is considered critical to assure that SHM systems are fully utilized after serving the purpose of a specific study. Survey results on industry’s preferences on visual data
representations and interest on novel visualization formats (e.g., holographic data projections) may suggest to SHM technology experts strategies to improve typical graphic formats and implement new approaches for data communication.
Usefulness of Structural Health Monitoring for the Wood Construction Industry: Global and Local Perspectives

by
Morvarid Dilmaghani

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Morvarid Dilmaghani, Author
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CONTRIBUTION OF AUTHORS

Dr. Christopher Sanchez directly contributed to the conceptual design of the questionnaire presented in Appendices: “Survey II”.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 General Introduction .......................................................... 1</td>
</tr>
<tr>
<td>1.1 Background and problem statement ........................................ 1</td>
</tr>
<tr>
<td>1.2 Research questions and goals ............................................... 4</td>
</tr>
<tr>
<td>1.3 Methodology ........................................................................... 5</td>
</tr>
<tr>
<td>1.3.1 Structural health monitoring of timber buildings: A review ....... 5</td>
</tr>
<tr>
<td>1.3.2 Applicability, usefulness and accessibility of monitoring data of mass timber buildings: stakeholder perceptions and preferences (Survey I) ..... 6</td>
</tr>
<tr>
<td>1.4 Outline of the thesis .............................................................. 7</td>
</tr>
<tr>
<td>2 Structural health monitoring of timber buildings: A review ........... 11</td>
</tr>
<tr>
<td>2.1 Introduction ............................................................................ 11</td>
</tr>
<tr>
<td>2.2 The development of official SHM documents: Theoretical framework for a SHM categorization ................................................................. 14</td>
</tr>
<tr>
<td>2.3 Methods and data .................................................................... 18</td>
</tr>
<tr>
<td>2.3.1 Data collection .................................................................... 18</td>
</tr>
<tr>
<td>2.3.2 Data analysis ...................................................................... 20</td>
</tr>
<tr>
<td>2.4 Results .................................................................................... 22</td>
</tr>
<tr>
<td>2.5 Discussion .............................................................................. 30</td>
</tr>
<tr>
<td>2.6 Conclusions ............................................................................ 33</td>
</tr>
<tr>
<td>3 Applicability, usefulness and accessibility of monitoring data of mass timber buildings: stakeholder perceptions and preferences .................. 45</td>
</tr>
<tr>
<td>3.1 Introduction ............................................................................ 45</td>
</tr>
<tr>
<td>3.1.1 Usefulness of monitoring data .............................................. 48</td>
</tr>
<tr>
<td>3.1.2 Access to monitoring data .................................................... 50</td>
</tr>
<tr>
<td>3.1.3 Available data visualization tools ......................................... 51</td>
</tr>
<tr>
<td>3.1.4 Who are the SHM users ....................................................... 54</td>
</tr>
<tr>
<td>3.1.5 The context of the study ....................................................... 56</td>
</tr>
</tbody>
</table>
TABLE OF CONTENTS (Continued)

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.2 Methods</td>
<td>57</td>
</tr>
<tr>
<td>3.2.1 Target population and sampling frame</td>
<td>57</td>
</tr>
<tr>
<td>3.2.2 Questionnaire and data collection</td>
<td>58</td>
</tr>
<tr>
<td>3.2.3 Data analysis</td>
<td>61</td>
</tr>
<tr>
<td>3.3 Results</td>
<td>61</td>
</tr>
<tr>
<td>3.3.1 Demographics</td>
<td>62</td>
</tr>
<tr>
<td>3.3.2 Perceptions on the applicability and usefulness of monitoring data</td>
<td>63</td>
</tr>
<tr>
<td>3.3.3 Perceptions on the accessibility and communication of monitoring data</td>
<td>69</td>
</tr>
<tr>
<td>3.4 Discussion</td>
<td>75</td>
</tr>
<tr>
<td>3.5 Conclusions</td>
<td>79</td>
</tr>
<tr>
<td>4 Overall discussion and conclusions</td>
<td>88</td>
</tr>
<tr>
<td>4.1 Limitations</td>
<td>90</td>
</tr>
<tr>
<td>4.2 Recommendations and a proposal for future research</td>
<td>91</td>
</tr>
<tr>
<td>Appendices</td>
<td>96</td>
</tr>
<tr>
<td>Appendix A Survey I instrument</td>
<td>97</td>
</tr>
<tr>
<td>Appendix B Survey II instrument</td>
<td>105</td>
</tr>
</tbody>
</table>
## LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>A visual explanation of a pattern in data sense-making</td>
<td>4</td>
</tr>
<tr>
<td>2.1</td>
<td>A Flow diagram of the process for selecting studies</td>
<td>19</td>
</tr>
<tr>
<td>2.2</td>
<td>Categories used for data analysis</td>
<td>22</td>
</tr>
<tr>
<td>2.3</td>
<td>Global distribution of SHM projects</td>
<td>23</td>
</tr>
<tr>
<td>2.4</td>
<td>Main study findings - Number of SHM projects within the survey analysis</td>
<td>25</td>
</tr>
<tr>
<td>2.5</td>
<td>Mid- and large-span structures under the “transport” and “Other” use categories</td>
<td>25</td>
</tr>
<tr>
<td>2.6</td>
<td>Study findings – Global distribution of different type of structures, by time period</td>
<td>26</td>
</tr>
<tr>
<td>2.7</td>
<td>Large-scale monitoring studies within the survey analysis categories</td>
<td>27</td>
</tr>
<tr>
<td>2.8</td>
<td>Number of SHM projects by building type/use category</td>
<td>28</td>
</tr>
<tr>
<td>2.9</td>
<td>Temporal development of monitoring projects of existing and new structures</td>
<td>28</td>
</tr>
<tr>
<td>2.10</td>
<td>a) Distribution of private and public monitored buildings, b) Clients of monitoring projects/data users</td>
<td>29</td>
</tr>
<tr>
<td>2.11</td>
<td>Number of SHM projects by client/user and scope of SHM</td>
<td>29</td>
</tr>
<tr>
<td>2.12</td>
<td>Number of SHM projects documenting data-based actions</td>
<td>30</td>
</tr>
<tr>
<td>Figure</td>
<td>Page</td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>------</td>
<td></td>
</tr>
<tr>
<td>3.1 Number of respondents with different occupations, years of experience and number of completed projects in the last five years</td>
<td>63</td>
<td></td>
</tr>
<tr>
<td>3.2 Respondent perceptions regarding usefulness of monitoring to support actions</td>
<td>64</td>
<td></td>
</tr>
<tr>
<td>3.3 Respondent perceptions on critical locations to monitor moisture content of timber</td>
<td>66</td>
<td></td>
</tr>
<tr>
<td>3.4 Respondent perceptions regarding critical locations to measure displacements</td>
<td>67</td>
<td></td>
</tr>
<tr>
<td>3.5 Respondent perceptions related to monitoring of vibration/seismic movement in different types of buildings</td>
<td>68</td>
<td></td>
</tr>
<tr>
<td>3.6 Preferences of respondents related to monitoring duration of timber buildings (monitoring durations were ordered from the most to the least preferred)</td>
<td>69</td>
<td></td>
</tr>
<tr>
<td>3.7 Preferences of respondents regarding the type of monitoring data to access</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>3.8 Respondent preferences regarding the type of accessibility to the monitoring platform</td>
<td>71</td>
<td></td>
</tr>
<tr>
<td>3.9 Respondents preferences regarding the type of tasks to perform with the monitoring platform</td>
<td>72</td>
<td></td>
</tr>
<tr>
<td>3.10 Perceptions of respondents regarding the usefulness of the data visualization Formats</td>
<td>74</td>
<td></td>
</tr>
<tr>
<td>3.11 Preferences of respondents regarding the type of access to monitoring data (types of access were ordered from the most to the least preferred)</td>
<td>75</td>
<td></td>
</tr>
</tbody>
</table>
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>List of questions, related research questions and type of analysis</td>
</tr>
<tr>
<td>3.2</td>
<td>Ranking of the factors impacting the service life of a timber building</td>
</tr>
<tr>
<td>3.3</td>
<td>Ranking of formats of monitoring data presentation</td>
</tr>
</tbody>
</table>
## LIST OF APPENDICES

<table>
<thead>
<tr>
<th>Appendix</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Survey I instrument</td>
<td>97</td>
</tr>
<tr>
<td>B. Survey II instrument</td>
<td>105</td>
</tr>
</tbody>
</table>
1 GENERAL INTRODUCTION

1.1 Background and problem statement
Over the years, wood construction industry and methodologies have changed and evolved due to structural developments, product developments, and material availability and demand (Hall and Flock, 2008). The change from dimension wood to engineered wood products represents a growing market for different types of construction. The wood construction industry is advancing in response to increased performance demands (Hall and Flock, 2008; Schmidt et al. 2018).

Mass timber construction represents both a return to more traditional forms of timber construction and an advancement in wood building technology that exceeds the structural limits of light frame wood construction (Mayo, 2015). Mass timber construction involves large-sized engineered wood products and these products have shown promise as an innovative alternative to reinforced concrete and steel systems for use in tall buildings (Mohammad et al. 2016).

With its abundance of forest resources and the existing manufacturing infrastructure, the Pacific Northwest is emerging as a hub in the U.S. for the development of the modern wood construction industry (Pei et al. 2016). While this industry is advancing in response to increased performance demands, it is necessary to assess the timber structural performance, and to characterize the real behavior of the timber structures (Cremona, 2016). It is also critical to validate current designs and provide benchmark data for future projects.

Structural health monitoring (SHM) entails the deployment of sensors and analytical tools to observe, measure, and analyze data related to the actual behavior of a structure, and check that this corresponds to the designed performance (Cremona, 2016). SHM is the process for detecting abnormal behavior of the civil structure based on quantifiable response parameters such as humidity, temperature, strain and acceleration over time (Cremona, 2013). The deployment of SHM can prolong the serviceability of
a structure and guarantee life-safety standards over its operational life. Additionally, in new construction, SHM systems can be used to evaluate the performance of new construction techniques/systems (Lynch, 2007). SHM can play a critical role in pushing structural engineering towards more effective, sustainable practices, allowing effective management of constructed facilities (Del Grosso, 2014).

Technological and methodological evolution of SHM has been accompanied by the development of technical SHM documents, starting with the publication in 2002 of the first guideline, proposed by the Canadian organization Intelligent Sensing for Innovative Structures (ISIS) (ISIS Canada, 2002). Most of the published technical documents, however, are focused on applications in modern civil structures and infrastructures built with steel or reinforced concrete. Despite this fact, SHM is also used for both traditional and modern timber structures. Some SHM applications for traditional timber structures provide useful information for the maintenance, repair or retrofitting of those structures (as presented in the next chapter of this thesis). As a matter of fact, a good SHM system should be able to early detect any structural damage, to optimize maintenance interventions and to prevent structural failure (Choi et al. 2007). SHM applications of modern timber structures can give important design information and such a system can provide a wealth of data for further studies and developments, and contribute to a database that can be used for future comparisons and design optimization (e.g., to update numerical models) (Fink and Kohler, 2011).

Despite the technological and theoretical developments available to date, SHM is still not extensively applied in the construction sector for a number of reasons. Del Grosso, (2014) reviews some of the major difficulties affecting the adoption of SHM technologies as a common engineering practice and points out that there is a need for developing a new generation of guidelines and standards. The author also mentions that extreme variety of the players involved in the construction sector including, facility owners, designers and contractors, poses difficulties to find a common interest in the implementation of SHM projects. There are also other potential difficulties for extensively applying SHM systems, such as the extreme variety of structural types and,
last but not least, a common lack of understanding of the potential benefits induced by the use of SHM techniques (Del Grosso, 2014). Lanata, (2015) states that the analysis level and accuracy at material scale to be used to catch the global structural behavior of timber structures is still unknown. Given the relative novelty of this field, Lanata suggests to document various SHM experiences into a guideline to let building developers, architects and structural engineers participate in planning and designing an efficient and useful monitoring system (Lanata, 2015).

For a monitoring system to be considered successful, it must be able to produce value to its stakeholders. Monitoring data need to be easily accessible, understandable, and transferable, in order to support informed decision and guide relevant stakeholders to choose the action that is most effective for a given situation (Glisic et al. 2014). Several authors agree that there is a high risk that the great amount of data gathered through sensors is underutilized by building stakeholders, as it is often not accessible or not comprehensible (e.g., Ciribini et al. 2017; Napolitano et al. 2018).

Recently, efforts have been made to develop effective ways to visualize and communicate SHM data. Current ways of accessing monitoring data include wired network, wireless communication via cell-phone network, web-user-interfaces enabling access to real-time data as well as historical time-series data (Ciribini et al. 2017), and on-site access from central dashboards (Furtner et al. 2013). Multifunctional platforms provide accessibility and visualization of meta-data and are used to configure sensors and associated reading units, extract data, set alerts, and create reports (Glisic et al. 2014). More recently, efforts have also been made to integrate visualization of sensor networks and data in virtual or augmented environments (Mustapha et al. 2018). These types of novel interfaces may provide access to raw and analyzed data, and relate visualization of data to additional information of a structure or of a SHM system (Napolitano et al. 2018). Besides traditional graphic formats, such as graphs and tables, whose effectiveness is discussed for instance by Johannessen and Fuglseth, (2014), alternative graphic representations have also been proposed to directly correlate temporal sensor readings with their corresponding spatial location (SMT Research Ltd.
GROUP, 2014). Little research has been done, however, to assess the effectiveness of these different visualization formats and communication tools to support decision-making processes.

In order to remove current barriers and make an advance in SHM applications of wood constructions and support decision-making processes of wood construction stakeholders, there is a need to:

1) Understand usefulness of SHM data for the wood construction industry;
2) Understand how SHM data of timber structures can be accessed and communicated to support decision-making processes.

1.2 Research questions and goals

While many studies state the potential of SHM data to inform decision-making processes of key stakeholders in the AEC industry, there is little evidence that the information embedded in SHM data is fully exploited. There is a need to understand:

a) The current use of SHM data by the wood construction industry;
b) Perceived importance of SHM to the wood construction industry and how it uses information from SHM data;
c) The extent to which SHM data reach the intended audience;
d) Which features of the currently available data visualization tools are considered useful by the targeted AEC users.

Figure 1.1 represents a visual explanation of a pattern in data sense-making to support decision-making processes of the stakeholders.

Figure 1.1: A visual explanation of a pattern in data sense-making (Fayyad et al. 1996).
Overall the goals of this research are to:

1. Understand current perceptions and awareness of the AEC industry on the applicability and usefulness of SHM data in wood construction, and in particular in mass timber construction.

2. Evaluate the preferences of the AEC industry regarding access to monitoring data and relevant information from a SHM project.

Findings of this research can contribute to development of strategies to effectively communicate SHM data to wood construction stakeholders. Findings of this study can also stimulate future research for the development of tools in SHM systems to support decision-making.

1.3 Methodology

In order to address these research questions, this study includes two main phases: 1) a literature review with the scope of identifying the main fields of application of SHM in timber buildings, the types of data produced and their use (research question a); 2) a survey among mass timber stakeholders in the U.S. Pacific Northwest, to address specifically research questions (b), (c) and (d). In this thesis, a preliminary design of a survey is also presented to evaluate effectiveness of typical SHM data presentation formats (i.e., graphs) to support decision-making.

1.3.1 Structural health monitoring of timber buildings: A review

In this phase, a systematic literature review was conducted based on a multi-staged iterative method. This included: defining review scopes, literature search, practical screening, quality appraisal, data extraction, analysis of studies, and writing the review (Okoli and Schabram, 2010). This synthesis of the literature covers peer-reviewed research articles and grey literature investigating SHM projects.

A deductive analysis was performed (Bandara et al., 2015), according to themes and sub-themes extracted from the analysis of the official SHM documents described in background. Therefore, data for the SHM projects of timber structures were analyzed.
considering both SHM- and building-related categories. SHM categories consisted in 1) scope of the SHM project, 2) investigated phenomena, 3) measurands (i.e., parameters used to analyze the investigated phenomena), 4) scale, and 5) duration of monitoring. Timber building-related categories were: 1) size of building, 2) main structural systems of the monitored building, 3) monitored system, 4) material of the monitored system, 5) building type/use, 6) age of structure, g) building owner.

1.3.2 Applicability, usefulness and accessibility of monitoring data of mass timber buildings: stakeholder perceptions and preferences (Survey I)

In this phase, a web-based survey was developed to investigate stakeholder perceptions on the value of SHM data and analyze their preferences on data access and visualization (presented in Appendix A). The target population of this study was designers (architects, engineers), contractors and manufacturers in the mass timber industry. In particular, the focus was the mass timber industry in the U.S. Pacific Northwest due to the fact that this region has the potential and the inherent strengths to be a national competitor in mass timber production markets (Oregon BEST et al. 2017). Participants in prominent initiatives promoting mass timber construction in this region, namely activities organized by the TallWood Design Institute (TDI) and the Mass Timber Conference (MTC), were a representation of this study target population. The TDI MeetUp is an informal monthly gathering, in the form of workshops and other continuing education and networking opportunities for building professionals interested in engineered wood products. The MTC attracts professionals from across the forest, manufacturing, design, development, and construction industries. This conference is the largest gathering of cross-laminated timber and other mass timber experts North America with a special focus on manufacturing and mid- to high-rise construction (https://www.masstimberconference.com/). Within the identified target population, subscribers of the TDI newsletter, and attendees and exhibitors in the conference, both prominent for the mass timber industry in the region, were selected as sampling frame. The sampling frame was defined considering: reasonable access, and potential interest to this study topic.
The questionnaire consisted of three sections: 1) demographic information, perceptions of: 2) the applicability and usefulness of monitoring data, and 3) the accessibility and communication of monitoring data. Questionnaire items in the second category generated considering factors impacting durability, safety, serviceability and performance of timber buildings. Questions investigating respondent’s preference on monitoring data format, accessibility, and visualization were generated considering functionalities currently available in commercial SHM database platforms and analytics software, as well functionalities and interfaces developed and tested in research studies reported in Chapter 3. The results of this survey can be used to develop effective data communication tools and strategies allowing for data-supported decision making for the design of new structures and the service life management of built facility. Additionally, knowledge of the perceived value of SHM data and expectations of stakeholders is instrumental to develop effective approaches for the design of SHM systems.

1.4 Outline of the thesis
Chapter 2 discusses the results of a literature survey aimed at investigating the current applications of monitoring projects of timber structures. Chapter 3 presents the results of a survey aimed to understand perceptions of a group of mass timber stakeholders on the value of SHM data, access to monitoring data, and usefulness of the currently available data visualization tools. The questionnaire is presented in Appendix A (Survey I). Chapter 4 discusses overall discussion and conclusions and future work of this study including the design of a survey to evaluate effectiveness of typical formats in supporting decision-making processes. “Survey II” is presented in Appendix B.
References


https://www.masstimberconference.com/
2 STRUCTURAL HEALTH MONITORING OF TIMBER BUILDINGS: A REVIEW

Abstract

In recent years, multiple historic and contemporary timber buildings have been instrumented with sensors to monitor the performance of wood products and novel engineering systems. However, there is a paucity of knowledge on how monitoring data supports decision-making by relevant stakeholders. For this reason, it is necessary to understand the main scopes and applications of monitoring projects, including how monitoring data is used to support decision-making processes and to advance design of timber buildings.

This chapter presents the results of a literature survey focused on timber structural health monitoring (SHM) projects. This survey was aimed at investigating how the scopes of monitoring projects are technically addressed and who are the primary users of SHM data. The main contribution of this study is the definition of a general taxonomy to describe timber SHM projects, their scope, approaches, and potential outcomes. This taxonomy aids readers in identifying ways of using information from SHM data. The results of this survey can be used to develop strategies allowing for data-supported decision-making for the preservation of historic buildings, the design of new structures, and the service life management of built facilities.

Keywords: Structural health monitoring, timber buildings, hygrothermal monitoring, structural monitoring.

2.1 Introduction

Historical timber structures document multiple generations of sustainable practices and craftsmanship. Condition assessment of historical timber structures is key to transmitting knowledge of these practices and preserving an increasingly important
built asset (Riggio et al. 2018). In addition, timber structures represent a growing market for different types of contemporary construction, e.g., large-span structures and multistory buildings. The wood construction industry is advancing in response to increased performance demands (Schmidt et al. 2018). Therefore, it is important to characterize the as-built behavior of timber structures and provide benchmark data for future designs. The process of monitoring and assessing the condition and reliability of structures is the core of structural health monitoring (SHM) (Cremona, 2016; Rücker et al. 2006a), and has been implemented in multiple projects for varying reasons. However, there is a lack of knowledge on how these SHM projects support decision-making of relevant stakeholders.

The main charge of SHM is to evaluate progression of phenomena that can lead to a diversion from the designed behavior of a structure. This implies an analysis of the actions on a structure and their effects on the structure’s behavior. In the interest of convenience, SHM of timber structures is categorized in two main areas in this section: hygrothermal and structural monitoring, and, depending on the type of action, environmental or mechanical, respectively. The hygrothermal properties of materials depicting heat, air and moisture (HAM) transmission and storage phenomena have a significant influence on the long-term performance and durability of construction materials and constructed facilities. To determine the durability and service life of wood structures, attention must be given to the deterioration mechanisms activated in wood dependent on HAM transport phenomena (Alsayegh, 2012). For this purpose, external environmental loads such as precipitation, solar radiation, wind, and internal environmental loads, such as relative air humidity and temperature, are measured along with the hygrothermal parameters of the wood materials, i.e., moisture content and temperature (Doudak et al. 2005). Modeling and simulation tools are available to designers, allowing them to generate different scenarios for how moisture is transported and stored within a material or assembly (e.g., ORNL, 2012). The seasonal and daily changes in temperature and relative humidity (RH) affect the moisture content (MC) of the wood. Dimensional changes of wood depend on MC. Shrinking and swelling generate stresses within the wood and lead to the propagation of cracks (Bjorngrim et
al. 2016; Franke et al. 2018). Generally, changes of MC in wood lead to changes of almost all physical and mechanical properties (e.g., electric properties, specific gravity, strength and stiffness properties) (Glass and Zelinka, 2010). Additionally, high or fluctuating levels of MC can have an impact on the long-term deformation of structural timber elements. This is due to a combination of viscoelastic and mechano-sorptive creep (Grossman, 1976; Muszyński et al. 2005). In addition, wood, as an organic material, is susceptible to biodeterioration. At a MC greater than 20%, wood is susceptible to surface fungal attack by molds. At MC greater than 25% (near the fiber saturation point), wood is at risk of chemical/structural damage by rotting fungi decay (Zabel and Morrell, 1992). Factors such as chemical interactions and corrosion, triggered by high MC, can also affect the performance of wood components (Hall and Flock, 2008). Hygrothermal monitoring can help in determining the preventative measures necessary to control the response of timber structures to HAM transport and their effect on their long-term performance (Alsayegh, 2012).

Structural monitoring is a process for determining how reliable the structure is at carrying both current and projected future loads. Information on the static and/or dynamic behavior of a structure can be acquired through one-time measurements, and periodic or permanent data acquisition. Monitoring characterizes time-dependent phenomena, and therefore, multiple data are typically acquired throughout the monitoring period of interest. One-time measurements of dynamic parameters are often used to support SHM tasks as well (e.g., vibration based damage identification of bridge structures and buildings using validated initial physical model of the structure) (Chen, 2018). In the design of a structural monitoring plan, it is essential to identify the most significant limit states, i.e., conditions exceeding the designed level of serviceability or safety of a structure. Parameters that can be measured to monitor structural conditions of timber structures include: dynamic parameters (e.g., accelerations), measurement of time-variant measures such as displacement, deformations (including vertical deformations and deflections), strains and stresses, and damage development (e.g., crack width). This is undertaken with the aim of
detecting changes in the structural properties and, in some cases, to be alerted when limit states are reached or exceeded (Rücker et al. 2006b).

This chapter presents the results of a literature survey aimed at investigating the current applications of monitoring projects of timber structures. The objectives of this study are twofold:

1) To review the main scopes and applications of monitoring projects, and how these scopes are technically addressed;
2) To understand how published SHM data is used to support decision-making processes.

2.2 The development of official SHM documents: Theoretical framework for a SHM categorization

This section introduces some technical SHM documents. These documents are used to identify commonly accepted categories, scopes, audiences, and accepted methods of SHM, as well as common terminology as a basis for the literature review. For this purpose, each document is presented in chronological order based on the date of release and in consideration of the following aspects: application field, target audience, and categories/terms used.

The guideline for structural health monitoring proposed by the Canadian organization Intelligent Sensing for Innovative Structures (ISIS) (ISIS Canada, 2002) is the first SHM guideline released in the world. The target audience of this document is structural engineers. The guideline presents methods applied for static and dynamic SHM of innovative structures, with a particular focus on bridges. Damage detection levels are based on the definition originally provided by Rytter (1993).

“Development of a Model Health Monitoring Guide for Major Bridges” was published in 2003 by the United States Department of Transportation (Aktan et al. 2003). The target audiences of this document are bridge engineers, consultants, owners, and
managers. This technical report provides a definition of performance, health monitoring, and structural identification used for this literature search.

The “Guideline for Structural Health Monitoring” (Rücker et al. 2006a) introduces existing procedures and technologies of structural assessment, and gives recommendations for their application. This document was extensively used in this survey to identify data analysis categories, such as phenomena and measured parameters (i.e., measurands). Recently, a compulsory technical code (GB 50982-2014) has been developed and implemented in China for structural health monitoring of buildings and bridges. The Chinese code highlights the importance of including SHM within the design phase, and enforces technical parameters corresponding to different applications of SHM. The code includes a key SHM vocabulary which was used to refine this literature search (Moreu et al. 2018).

While all the above technical documents are material-independent, they are mainly focused on applications on modern civil structures and infrastructures built with steel and reinforced concrete. Only recently have efforts been made to address specific needs of SHM of timber structures. An example of these efforts is the activity of the working group “Monitoring of Timber Structures” within the Cost Action FP1101 (D’Ayala et al. 2014).

From the analysis of the cited SHM technical documents, the identified scopes of SHM as a tool to support decision-making, are to:

i) inform immediate actions in case of a major event i.e., (a) damage assessment;

ii) inform immediate or differed actions in case of doubts on the current structural performance, i.e., (b) safety and serviceability assessment;

iii) predict future performance for cost-effective scheduling of inspections, maintenance, and repairs, i.e., (c) service life planning; and

iv) validate new design, i.e., (d) performance evaluation, and (e) numerical model validation/calibration.
The terms used for the definition of the SHM scopes are further specified below.

(a) **Damage assessment:** According to the definition provided in the SAMCO guidelines, damage can be referred to as “changes introduced into a system that adversely affects current or future performance” (Rücker et al., 2006a). This definition is limited to changes to the material and/or geometric properties of structures, including changes to boundary conditions and systems compatibility. Damage assessment is performed to evaluate the presence and extent of damage or capacity loss caused by a natural or man-induced event. In these guidelines, applications of SHM for damage assessment are defined as evaluating one or more of the following items: damage magnitude, damage consequences, damage development, and damage cause (Rücker et al. 2006a).

(b) **Safety and serviceability assessment:** In ISO 2394 (1998), “safety” is defined as the ability (of a structure or structural member) to avoid exceedance of ultimate limit states, including the effects of specified accidental phenomena, with a specified level of reliability, during a specified time period. In this standard, “serviceability” is defined as the ability of a structure or structural member to perform adequately for normal use under all expected actions. To ensure the safety and serviceability of the structure, deformations, stress values, and damage such as cracks, need to be limited (Rücker et al., 2006a). Structural health monitoring aimed at serviceability and safety assessment provide data to support decision-making for possible interventions when the structural safety or serviceability is shown to be inadequate. The results of the assessment should be used to recommend construction interventions (ISO 13822, 2010).

(c) **Service life planning:** In ISO 15686-1 (2011), “service life” is defined as the period of time after installation during which a structure or its parts meets the performance requirements, whereas the term “performance” refers to the qualitative level of a critical property. Thus, service life is a timespan ending when a critical property becomes too low to fulfill performance requirements, e.g., structural safety or serviceability. This standard also specifies that “service life planning” is a design process that seeks to ensure that the service life of a
building or other constructed asset will equal or exceed its design life. If required, service life planning can take into account the environmental impact(s) on the building. Service life planning can also be used to make decisions on maintenance and replacement requirements, and to estimate or predict the service life of a building’s components.

(d) **Performance evaluation:** The scope of performance evaluation includes evaluating performance of structures that encompass new construction techniques, unique materials, and novel building practices (Mustapha et al. 2018). According to Aktan et al. (2003), “performance” is “the fulfillment of a promise.” Specification of the objective and quantification of each limit-event are important issues related to the definition of performance. Determining measurands and proper assessment methods are critical for guaranteeing that the desired performance limits will not be exceeded in the limit-events expected during the life cycle of a structure. According to performance-based engineering, “Performance characteristics of the constructed facility are described in terms of rational and measurable quantitative indicators, and these characteristics become the actual deliverable” (Aktan et al. 2007).

(e) **Model validation/calibration:** Different types of analytical and numerical models can make use of SHM data. One of the main application fields is structural identification based on dynamic monitoring data. Aktan et al. (2003) define “structural identification” as “the development of an analytical conceptualization leading to an analytical model of a structure that is quantified, tested, and validated by correlating model simulations with corresponding measurements from the structure.” Damage models for predicting the service life of a component can be based on SHM data as well (e.g., monitoring environmental loads in dose-response models) (e.g., Bastidas-Arteaga et al. 2015). Predictive models of the long-term behavior of timber structures make use of both structural and environmental monitoring data (e.g., deflections, moisture content, relative humidity, temperature). These models are used to analyze wood rheological phenomena such as viscoelastic creep, mechano-
sorptive creep, shrinkage, and a combination thereof (e.g., Schaffer, 1972, Schänzlin, 2010, and Granello et al. 2019).

2.3 Methods and data

2.3.1 Data collection

A systematic literature review was conducted based on a multi-phased iterative method. This included: defining review scopes, literature search, practical screening, quality appraisal, data extraction, analysis of studies, and writing the review (Okoli and Schabram, 2010). This synthesis of the literature covers peer-reviewed research articles published in English within international scientific journals, conferences, and scientific theses. Research articles investigating Structural Health Monitoring (SHM) projects were collected using Google Scholar and Scopus, both of which have a wider coverage for scientific articles than any single publisher’s database. It is worth mentioning that even though conference papers are usually considered a lower rank source than peer-reviewed international journals, they can report projects at their early stage of implementation. This was an important source of information for our study. In addition to scientific literature, grey literature was considered to capture relevant non-academic, industry-driven research efforts on the studied topic. Common grey literature publication types include reports, working papers, government documents, white papers, and evaluations.

Our systematic literature search followed three steps. In the first step, internet searches were used to find relevant articles based on their titles using the word “monitoring” combined with one or more other search keywords. The keywords “timber buildings” or “timber structures” were used in combination with the following keywords in the literature search: structural monitoring, hygrothermal monitoring, dynamic monitoring, field measurement, hygrothermal performance, structural performance, dynamic performance, vibration tests, damage assessment, service life, and environmental performance. Altogether, 250 rounds of searches with different search word combinations were implemented to ensure that all relevant articles were included. A total of 130 articles were identified in the first search step.
Once the lists were cleaned for double-counting, book reviews, abstract overviews and editor’s notes were excluded, this resulted in a database of 107 articles. In the second step, abstracts of identified articles were examined. The 107 articles were reduced to 73 articles after 34 articles were rejected for one of the following reasons:

- The word ‘monitoring’ was used in explaining methodology and design of field experiments, but not in implementation within a building;
- Included monitoring projects were not timber structures;
- The word ‘monitoring’ referred to energy-efficiency analysis or evaluated timber fire performance, and not to hygrothermal or structural monitoring, according to the definitions provided in the Introduction;
- The word ‘monitoring’ was used in explaining sensor network technology.

In step 3, the contents of these 73 articles were read in full and the review snowballed to 89 after pursuing 16 additional papers listed among citations included in our sampled articles. Among these 89 articles 18 articles were further excluded. The final database covers 71 articles written within a timespan from 1988 to 2019. Figure 2.1 represents a flow diagram as a summary of the process for selecting studies.

Figure 2.1: A flow diagram of the process for selecting studies.
2.3.2 Data analysis

Results of the literature search were recorded in a spreadsheet, which initially included basic information for each entered document (i.e., citation information; the name of the project/building; its geographic location; the date of the SHM installation if available, or of the oldest retrieved document reporting that project; a synthesis of the research questions and main findings; a hyperlink when possible). Additional columns were added to the spreadsheet to categorize each document according to our study’s objectives. A deductive analysis was performed (Bandara et al., 2015), driven by the themes and sub-themes identified from the objectives of this study, and extracted from the analysis of the official SHM documents described in section 2. Therefore, the following categories were analyzed: 1) scope of the SHM project, 2) investigated phenomena, 3) measurands (i.e., parameters used to analyze the investigated phenomena), 4) size of building, 5) building type/use, 6) age of structure, g) building owner / SHM data user (Figure 2.2).

The principal category considered in this study is the scope of monitoring, which was determined according to the definitions provided in the theoretical background. Accordingly, SHM scopes are classified into main five groups: (a) damage assessment, (b) safety and serviceability assessment, (c) service life planning, (d) performance evaluation, and (e) numerical model validation/calibration. In some documents, more than one scope was attributed either implicitly or explicitly to a single project. In this case, all SHM scopes attributed to a project were accounted for in the data analysis. The second category focused on the observed phenomena expected to lead to a diversion from the designed behavior of a structure. Four main groups were identified within this third category: hygrothermal behavior/durability, dynamic behavior, viscoelastic behavior, and damage development. The third category focused on the measured parameters. This category includes static (e.g., deformations, displacements, rotations, strains, etc.), dynamic (e.g., accelerations), and environmental measurands (e.g., air temperature, RH, etc.), as well as physical material parameters (i.e., wood MC).
Regarding the fourth category, it was decided to classify structures into four main groups reflecting the dimension and scale of the building: (a) multistorey buildings (e.g., low- mid- high-rise), (b) single-storey buildings, (c) mid-span structures, and (d) large-span structures. The fourth group in this category includes structures such as hall roofs, bridges, etc., with a span larger than 30m and whose main structural system is a bending structure, such as plate girders and trusses, or with members in pure compression, such as arches, multiple-arch vaults, ribbed domes, etc. (Crocetti, 2016).

Building occupancy classifications are based on a building’s usage and are typically defined in model building codes (e.g., IBC-ICC 2018). These classifications have been used to define a possible list of building types in the fifth data category: (a) residential, (b) commercial (e.g., office, retail, hotels, sport facilities, theaters, etc.), (c) agricultural/industrial, (d) institutional (e.g., education, civic, religious, government, military, etc.), and (e) transport (e.g., bridges, station, etc.). In the sixth category, structures are classified into two groups: new and existing.

The last category identifies building owners and primary users of the SHM project. Two general types of clients may commission a SHM project: public and private. Bolognani et al. (2018) identify two different decision-makers in a SHM project: the building manager, who uses monitoring data to make decisions regarding the structure; and the owner, who chooses whether or not to invest in a monitoring system to support a building manager’s decisions. While these two decision-makers can be the same in many cases, knowledge of their nature can be useful in quantifying SHM benefits, using the concept of value of information (VoI) (Bolognani et al. 2018). Literature data used in this survey was not detailed enough to deduct who the decision maker was, however, a correspondence between the initial scopes of monitoring and consequent actions taken was investigated. Scientific literature reports many research-driven SHM efforts, which are also considered in the last category of data, and distinguished from industry-driven project. These categories are summarized in Figure 2.2.
It is worth mentioning that two papers included a high number of monitoring projects (Dietsch et al. 2015; Hafeez et al. 2018). A separate analysis of these projects has been conducted, since the concentration of the SHM projects reported in these two works may skew the results.

2.4 Results

The research presented in this chapter investigated a total of 193 monitored timber structures from 1980 to 2019, in a variety of countries across Europe, North America, Oceania and Asia. The results reveal a lack of monitored structures in Africa, and South America (depicted in Figure 2.3). The projects were concentrated more in North America (92 of the total 193), than in Europe (79 of total). There were eighteen cases in Asia and just four cases in Oceania.
Figure 2.3: Global distribution of SHM projects.

Figure 2.4 visually illustrates the main statistical findings of the survey. The highest to lowest number of monitoring projects in each category is shown with the color from dark to light, and the size of the squares increases with increasing numbers of projects. As can be seen, monitoring data from a total of 18 single-storey buildings was mostly used for service life planning and, secondarily, to validate/calibrate numerical models, while most of the multistorey buildings were monitored to validate/calibrate numerical models. It is worth mentioning that most of these multistorey buildings were low-rise buildings. A smaller number of multistorey buildings (33) were monitored to evaluate their performance, i.e., to collect data to support performance-based design. Just eight multistorey buildings were monitored for safety/serviceability assessment purposes and eight for service planning. Monitoring data from large-span structures was mostly used for service life planning (28) and to assess their safety/serviceability (28). The latter category is also the main SHM scope for mid-span timber structures. Many of those mid- and large-span structures are under the “transport” use category (i.e., timber bridges). As shown in Figure 2.5, from a total of 40 mid- and large-span structures monitored to assess their safety/serviceability, 37 of them are bridges (under the “transport” use category). As expected, the hygrothermal behavior/durability phenomena were mainly investigated within the scope of service life planning, and, secondarily, to assess safety/serviceability. The related measurands of interest were
wood moisture content, air temperature, and air relative humidity. In a smaller group of buildings (13), monitoring of hygrothermal phenomena was aimed at evaluating a building system performance (for instance, moisture behaviour during construction, etc.). Dynamic behavior phenomena were mostly investigated in multistorey buildings in order to validate/calibrate numerical models. In this case, accelerations were the related measured parameters. Dynamic behavior of a small group of buildings (3) were monitored for service life planning to evaluate damage development; all of them were mid- and large-span structures. Viscoelastic behavior as a phenomenon was mostly investigated to predict structural performance (for instance, to evaluate the long-term behavior of pre-stressed timber systems) and, secondarily, for safety/serviceability assessment (e.g., to assess excessive floor deformations, etc.). The former group includes a total of 34 cases, 24 of which were large-span structures.

Wood moisture content, air temperature, and air relative humidity were measured in 91, 64, and 60 timber structures respectively, out of a total number of 193 investigated projects. Strains were measured in a 29 structures, which included twenty-two large-span structures, six low-rise multistorey buildings, and just one mid-span structure. Deformations were mostly measured for safety/serviceability assessment rather than for performance evaluation. As mentioned before, acceleration was mostly measured to validate/calibrate numerical models, and only secondarily as a means to evaluate building performance, i.e., collect data to support performance-based design.
Figure 2.4: Main study findings - Number of SHM projects within the survey analysis categories.

Figure 2.5: Mid- and large-span structures under the “transport” and “Other” use categories.

Figure 2.6 shows the temporal and geographic distribution of monitoring projects for different types of structures. Most projects between 1980 to 1989 are located in North America and all of them were large-span timber bridges. Several large-span timber structures were monitored in Europe between 2010 and 2019. These structures included 25 of the 193 SHM projects, 15 of them commercial buildings, six and four, respectively are agricultural/industrial buildings and bridges. The total number of
large-span timber structures monitored worldwide was 61, 36 of which are located in Europe: within this group, 21 monitored large-span timber structures are reported in one single research project (Dietsch et al. 2015).

A high number of multistorey buildings have been monitored in North America in recent years (52 cases out of a total of 100 worldwide). These structures included 23 low-, 28 mid- and just one high-rise buildings. Forty-five of them correspond to a large-scale monitoring study performed in Canada and are presented in Hafeez et al. (2018) (illustrated in Figure 2.6 as a superimposed, lighter circle – circle size corresponding to the sample size).

![Figure 2.6: Study findings – Global distribution of different type of structures, by time period.](image)

Figure 2.7 illustrates the statistical findings of the survey in the frame of the two above-mentioned published works referring to large-scale monitoring efforts (Dietsch et al. 2015; Hafeez et al. 2018). A large-scale, SHM study performed in Canada investigated the dynamic behavior of light-frame timber buildings by measuring accelerations. This allowed the evaluation of the building code formula used for the seismic analysis of this type of construction and provided a simplified modeling approach (Hafeez et al. 2018). Dietsch et al. (2015) studied the monitoring data of 21 large-span timber structures (namely, halls with large-span timber roofs) located in Germany. The
category of use for these buildings was either commercial (13 sport facilities) or agricultural/industrial (8 buildings total). All these structures were monitored within the scope of service life planning to evaluate how the hygrothermal behavior of the investigated timber roofs, when exposed to different climatic conditions, could be conducive to degradation and crack development. Wood moisture content, air temperature, and air relative humidity were measured for this purpose.

Figure 2.7: Large-scale monitoring studies within the survey analysis categories (Dietsch et al. 2015; Hafeez et al. 2018).

Figure 2.8 illustrates types of monitored buildings. As can be seen, most of the cases (79) were residential buildings. Fifty-three transport structures (i.e., bridges) and 33
commercial buildings are also included in this survey. A lower number of projects included institutional buildings (16) and agricultural/industrial buildings (12). It is worth mentioning that 47 of the 79 residential buildings were investigated in the large-scale study reported by Hafeez et al. (2018) (Figure 2.7). Without considering this large-scale study, the highest number of monitoring projects were of transport structures, followed by commercial buildings, residential, institutional building, and agricultural/industrial types.

![Figure 2.8: Number of SHM projects by building type/use category.](image)

As can be seen in Figure 2.9, the number of monitored new buildings (107) was higher than the number of monitored existing buildings (86).

![Figure 2.9: Temporal development of monitoring projects of existing and new structures.](image)

Figure 2.10a shows that 57% of the monitored structures are private buildings (110). Figure 2.10b illustrates the nature of monitoring data users. For most of the documented projects this information was not explicitly reported, however, it was possible to identify 59 industry-driven projects and 25 research-driven projects.
Figure 2.10: a) Distribution of private and public monitored buildings, b) Clients of monitoring projects/data users.

Figure 2.11 illustrates that primary data users of 18 cases out of a total of 59 industry-driven projects were owners of buildings. SHM was used to assess structural safety/serviceability (14) and damage (4). It is worth mentioning that all of these cases were public, existing buildings. Furthermore, the figure shows that all research-driven projects (25) were aimed to evaluate a building performance (15) and/or to validate/calibrate numerical models (10). It should be noted that all of these buildings were new buildings, and in some cases, both scopes were attributed to a single SHM project. Several case studies confirm correspondence between the initial scopes of monitoring and consequent actions taken, based on the information provided by the SHM data (Figure 2.12).

Figure 2.11: Number of SHM projects by client/user and scope of SHM.
2.5 Discussion

Most monitoring projects in the last decade are located in North America. These projects targeted mostly new buildings (monitored during construction and/or shortly after commissioning) to evaluate the performance of new construction techniques/systems. This scope is justified by the need for collecting empirical data on the condition of components and access to the real-time status of the structure during construction. This provides critical information for making informed decisions to either validate the extant design or improve future design. Data recorded during the life of the building helps validate the design decisions made and determine the viability and feasibility of the design (Mustapha et al. 2018). Europe also represents a high number of SHM projects, partially due to the large built asset and rich cultural heritage of this continent. Depending on the local construction tradition, either whole wood buildings or timber systems within non-wood buildings (e.g., timber floors and roofs in masonry structures) comprise this inventory. Forty-two of these cases were in fact existing/historic timber structures which were monitored to assess their safety/serviceability or to plan their service life. The latter scope is justified by the need for collecting data to support decision-making for the maintenance of a built asset (Bignotti, 2013); the former type of assessment is required when a change in the building use is planned, in case of suspected or visible damage, and to inform any intervention in a structure (Riggio et al. 2018). The lower number of monitoring projects in Asia and Oceania is not necessarily due to the quantity of timber structures in these regions; Asia is in fact a continent with a rich wood construction tradition (Min et al., 2013). It is worth mentioning that 14 of the total 18 monitored buildings in Asia were low-rise multistorey buildings, the majority of which traditional construction. Eighty-six percent of these buildings were monitored in the last decade.
In the last decade, there has been a clear increase in the number of monitoring projects across all types of structures (133 of total). This is likely due to the technological advancement of sensors and monitoring equipment. In particular, the number of multistorey timber buildings is increasing with time, and this phenomenon can be expected to continue into the future. This is due to the fact that the wood industry has experienced significant technical advances, first in Europe and soon followed by North America, Asia, and Oceania (Turner et al. 2006). These advances mainly consist of the development of new wood-composite materials and engineered wood products (Mohammad et al. 2016) and revision of codes to allow new heights and types of timber buildings (Karacabeyli and Lum, 2014, Hunt, 2018). Engineered wood products (EWPs), such as glued laminated timber, cross-laminated timber, laminated veneer lumber, and laminated strand lumber, are increasingly incorporated as structural elements within mid- and high-rise construction and large-span structures in Europe and North America.

As a result, more new timber structures have been monitored to respond to increased performance demands and to provide data for alternate design paths (Schmidt et al. 2018). Fifteen cases in this survey are mass timber buildings featuring different types of EWPs. The survey results also show that most of the multistorey buildings were monitored to validate/calibrate numerical models. Monitoring data is particularly crucial to scale-up laboratory test results. Such test results are typically obtained using small-scale samples (Arda Buyuktasakin et al. 2019), under known boundary and climate conditions, and in a limited timeframe. As applicability of laboratory data for predicting the behavior of an actual structure is limited, SHM data is fundamental to accounting for long-term effects and changes in climate conditions.

Monitoring data of large-span structures was mostly used for service life planning of bridges. This is not surprising as official SHM documents were first issued to monitor this type of infrastructure. Bridges need to be monitored to avoid exceeding ultimate limit states (such as deformations, cracks, etc.) over time. Service life planning is a
critical task for these type structures to support their maintenance. Recurrent visual inspection of bridges is a common practice; it is now often complemented or replaced by instrumental monitoring (Tannert et al. 2011). This is a result of the recent technological advances of sensors and novel data analysis algorithms for sensor networks (Lynch and Loh, 2006).

Wood moisture content, air temperature, and air relative humidity were the most commonly measured parameters, with the last two measurands often used to derive the former (i.e., with the so-called hygrometric method, Simpson, 1973). This is expected given the influence that wood moisture content has on the physical and mechanical properties of the material, and on the long-term performance and durability of timber buildings (Alsayegh, 2012). This data can be directly used to derive information about deterioration mechanisms and, consequently, make decisions on maintenance and replacement interventions, as well as estimating the service life of a building’s components (ISO 15686-1, 2011). Moisture content values and climate data are also used to calibrate other measurements and apply correction factors (Dietsch et al. 2014).

In thirty-three SHM projects, decisions taken based on monitoring data were clearly specified. In some projects, more than one scope of SHM was attributed to a single project. Data-based actions were mostly taken in buildings monitored for safety/serviceability assessment purposes.

In most of the published work, the nature of the client of the SHM project is not specified (58% of total). In 12.5% of these cases, the building’s client or the data users are a research entity/university. For those projects in which this information is reported, public clients, such as owners of existing/historic buildings or bridges, commissioned a SHM project to assess the structure’s serviceability/safety and damage, and eventually take a decision on types of short- or long-term intervention (e.g., immediate repair, maintenance, etc.).
2.6 Conclusions

A literature survey focusing on timber structural health monitoring (SHM) projects examined in detail seventy-one (71) papers documenting monitoring of 193 timber structures from 1980 to 2019. This literature survey provides a general taxonomy to describe timber SHM projects by identifying the most relevant scopes of monitoring and the types of data used for each scope. This taxonomy aids readers in identifying ways of using information from SHM data.

The survey also highlights trends in the nature and scope of monitoring of timber structures over the course of the reported period. A clear increase is noticeable in the number of monitoring projects undertaken in the last decade, with a relatively recent shift from Europe (mostly of existing buildings) to North America (mostly of new buildings). If this positive trend will continue in the future, identifying the main scopes and methods of SHM will become more and more critical for maintaining expected performance levels of a timber structure during its life cycle and support decision-making.

Two main categories of data users are identified in this survey: owners of public buildings and researchers. For the first category, the value of information provided by the monitoring data is often related to the historical/cultural or infrastructural value of the structure; in many cases, SHM data provided useful information for the maintenance, repair or retrofitting of those structures. The second category included new buildings and the value of information provided by the monitoring data is often related to developing, confirming, or improving methods of design; comparing design assumptions with the real behavior of a system; and supporting experimental/laboratory studies.

The majority of the reported SHM projects are research-driven. There may be different explanations for this, for instance: 1) the survey reports “published” SHM projects, and therefore reflects activities conducted by researchers; more timber structures than those included in this survey may have been monitored by and for non-research entities, but
not documented in publications; 2) SHM technology and methods are still not accessible to the general public and for the most common timber buildings; and 3) value of information of SHM data is still not fully considered by stakeholders beyond academia.

A limitation of research-driven SHM projects is the potential hiatus between data production/analysis (by the researcher) and consequent decision-making (e.g., depending on the scope of monitoring, by the building owner, the designer, the building official, etc.). A risk of research-driven over “decision-maker”-driven SHM projects is that SHM systems can be underutilized or even dismissed after serving the purpose of a specific study (rather than serving the “scope” of the monitored building).

Results of this survey are limited to works published in English. Moreover, despite the efforts of the Authors of reaching saturation in the literature search, some papers may have been omitted in this survey. As sometimes one single paper reported several projects, one omission may potentially affect the presented results considerably.

References


3 APPLICABILITY, USEFULNESS AND ACCESSIBILITY OF MONITORING DATA OF MASS TIMBER BUILDINGS: STAKEHOLDER PERCEPTIONS AND PREFERENCES

Abstract

In recent years, multiple mass timber buildings have been instrumented with sensors to monitor the performance of advanced engineered wood products and novel engineering systems. Many of these structural health monitoring (SHM) projects are research-driven. Research-driven projects are published SHM projects documented in publications. These projects reflect activities conducted by researchers. There is a need to understand current perceptions and awareness of the Architects, Engineers, and Construction (AEC) industry, with a stake in mass timber construction, on the applicability and usefulness of monitoring data to support informed decisions and advance design of mass timber buildings.

The aim of the survey presented in this chapter was to analyze perceptions of a selected group of mass timber stakeholders on the value of SHM data. The survey also investigated which features of the currently available SHM platforms and data visualization tools were considered useful by AEC users for a range of different monitoring applications. The results of this survey can be used to develop effective data communication tools and strategies allowing for data-supported decision making for the design of new structures and the service life management of built facilities.

Keywords: Mass timber, Structural health monitoring, Monitoring data, Value of Information.

3.1 Introduction

“Mass timber” refers to large linear or panelized engineered wood construction products such as glue-laminated timber (glulam) and cross laminated timber (CLT)
Mass timber products have shown promise as an innovative alternative to reinforced concrete and steel systems for use in tall buildings (Mohammad et al. 2016), and the last decade has been marked with a rise of interest and use of these products in North America (Pei et al. 2016, and Goubran et al. 2019). Recently, the International Building Code has been revised to allow to prescriptively design timber buildings up to 18 storey high (IBC, 2019). Prior to the new code, the approval process for tall wood buildings in the USA was done under the “Alternative Solutions” path, which is typically accomplished through extensive testing and engineering analysis (NRCC, 2010). One of the perceived factors preventing the use of mass timber for multi-storey constructions has been a limited knowledge base regarding long-term structural performance, and moisture durability (Conroy et al. 2018; Gosselin et al. 2017; Schwarzmann et al. 2018). As mass timber structures move to the forefront of sustainable design, continuous monitoring of these structures is extremely valuable for more informed design of mass timber buildings (Schmidt et al. 2018; Mustapha et al. 2018). However, the prominent motivation for monitoring of mass timber buildings is a general lack of knowledge of how this form of construction performs from an environmental perspective (Crawford and Cadorel, 2017).

Built structures are exposed to environmental conditions, the aging of their components or constitutive materials, and changing or exceptional loading effects, which may alter the intended performance of a building. The process of determination, monitoring and assessment of the level of service of structures is the core of structural health monitoring (SHM) (Cremona, 2016). Chapter 2 of this thesis presented that over the last decades SHM systems have been implemented in multiple timber building types for varying purposes. According to findings of this research, there has been a noticeable increase in the number of monitoring projects undertaken in the last decade, especially of new projects, featuring novel timber systems and materials (presented in the previous chapter). It was remarked that identifying the main scopes and applications of SHM of timber structures was critical for maintaining expected performance levels of a timber structure during its service life and supporting decision-making.
Multiple studies have illustrated usefulness of SHM data and have identified potential beneficiaries in the industry (Anderson and Vesterinen, 2006; Webb et al. 2015). Among the potential benefits of SHM there is the possibility to acquire data that can help mitigate risks associated with hazards, such as earthquakes and strong winds, support maintenance or structural safety evaluation of existing structures, rapidly evaluate conditions of damaged structures after an event, estimate residual life of structures, inform decision to repair and retrofit existing structures, and support design improvements for future structures (Rainieri et al. 2008).

SHM is basically an activity where actual data related to structures is observed, measured, recorded, processed and analyzed to check that a structure behaves as intended (Cremona, 2016). Data associated with a SHM project need to be easily accessible, understandable, and transferable (Glisic et al. 2014). Otherwise, there is a risk that the great amount of data gathered through sensors may be not fully utilized by building stakeholders, as it is often not accessible or not comprehensible (Ciribini et al. 2017). Without the ability to communicate monitoring data efficiently, an SHM system can be underutilized, or even abandoned (Napolitano et al. 2018), and data misunderstood. Therefore, for a monitoring system to be considered successful, it must be able to produce value to its stakeholders. Currently, guidance for designers of SHM systems is scarce, leading to many examples of poorly considered systems providing little or no real benefit (Webb et al. 2015). Additionally, there is a paucity of knowledge on how SHM data support decision making of relevant stakeholders. Therefore, the overall goals of this research were to:

1) understand current perceptions and awareness of the Architects, Engineers, and Contractors (AEC) industry on the applicability and usefulness of monitoring data to support informed decision and advance design of mass timber buildings,

2) evaluate the perceptions of the AEC industry regarding access to monitoring data and relevant information from a SHM project, and

3) understand which features of the currently available data visualization tools were considered useful by the AEC users for a range of different monitoring applications.
The following sections were intended to describe research exploring measurable and perceived usefulness of monitoring data, available ways to access to monitoring data, currently available data visualization tools, and who the SHM users are.

3.1.1 Usefulness of monitoring data

SHM data are intended to provide information, allowing a building manager or operator of a facility to implement an efficient maintenance plan or to devise extraordinary measures on a structure. SHM data can be also used to “learn” from a case study, i.e., a building, and apply the lesson learned to inform the design of new buildings, according to a performance-based design approach (e.g., Glaser and Tolman, 2008). The effectiveness of SHM systems depends on their capability to guide towards the most optimal decision for a given circumstance, avoiding errors and waste of resources. To do so, SHM data must be properly collected, processed, and accessed (Pozzi and Der Kiureghian, 2011).

Recently, a body of research has been dedicated to rank and quantify the Value of Information (VoI) of SHM, using a utility-based metric (e.g., Pozzi and Der Kiureghian, 2011; Thöns and Faber, 2013; and Qin et al. 2015). The value of a piece of information depends on its ability to guide our decisions, i.e., help us select the choice that is most desirable for the given circumstances. Most SHM studies only address the accuracy of the information derived from tests or sensing devices. The criteria guiding decisions a manager makes are often based on economic considerations: the relation between utility, outcome and action is quantitatively evaluated, making use of the information derived by sensing systems, when they are available. Value of information criteria are developed to help decision-makers to select the best action for the maximum expected utility (Pozzi and Der Kiureghian, 2011).

The important field of SHM-VoI study aims to provide ways of navigating trade-offs in decision-making processes between knowledge (based on SHM data) and utility (resources available and at risk). However, a fundamental problem persists in ensuring that SHM data can properly provide information, and that this can be synthesized into
knowledge to support action (Zins, 2007). An identified barrier to SHM implementation and use is stakeholder confidence in SHM data (Kijewski-Correa and Kareem, 2007). Stakeholder confidence has not advanced at a rate commensurate with the advances in sensor and information technologies, and without this confidence, SHM may remain largely an academic exercise. According to Kijewski-Correa and Kareem (2007), experiences in a full-scale monitoring program performing serviceability/habitability assessment, stakeholder confidence in SHM technologies varies greatly, depending on the hazard zone (e.g., raising concerns due to earthquakes). There are fiscal benefits perceived by ownership that motivate the investment in monitoring. In regions outside of seismic areas where serviceability/habitability limit states govern, owners see no fiscal incentive for monitoring, since assessment and reoccupation are non-issues. Thus, unless there are suspicious of a building impaired performance, e.g., excessive vibrations disruptive to occupants, owners will not invest in instrumentation. According to Kijewski-Correa and Kareem (2007), through the support of the research-driven projects, owners are often receptive to no-cost monitoring to learn more about the performance of their building and use the real-time data streams for maintenance and operation; however, they have significant concerns about fiscal losses that could result if the building is negatively perceived by the public.

Nepomuceno et al. (2018) describe a recent survey done prior the deployment of a monitoring plan of a footbridge to take into account stakeholder expectation requirements. The study quantified the likeliness of an SHM system to yield value to three key stakeholders: the ‘SHM engineer’, the ‘structural engineer’ and the ‘asset owner’. The results showed that a deployment of accelerometers was expected to provide the highest value to the asset owner, since it was considered a robust system, able to collect data that can inform the validation of design models, and inform bridge maintenance. Strain gauges were considered of less value to the asset owner, while structural engineers considered useful the strain data for model validation (Nepomuceno et al. 2018).
The aim of the survey presented in this chapter was to understand perceptions of a selected group of mass timber stakeholders on the value of SHM data. Knowledge of the perceived value of SHM data and expectations of stakeholders could be an instrumental to develop effective approaches for the design of SHM systems and collect data that can support decision making processes.

3.1.2 Access to monitoring data

Depending on the scope of monitoring, data can be accessed in different ways. Wired sensor networks use dedicated cabling to provide both power and data connectivity. These systems are usually very reliable and are capable of high data collection rates. The cost of cabling and installation time is a significant disadvantage with wired systems, as is the fact that sensors cannot readily be added or moved to different locations on the structure if desired. However, a wired system may be the most cost-effective solution for a SHM system intended to have a long service life, and that is installed during construction (Webb et al. 2015). Currently, wireless communication via cell-phone network and internet is a common technology. Through a web-user-interface, a user is enabled to access information concerning real-time data as well as historical time-series data (Ciribini et al. 2017). Online access from a registered account is also a way to remotely access monitoring data. A project dashboard provides an overview of the structure, the monitoring task and, possibly, existing notifications. Monitoring data shown at the web-user interface may be downloaded and subsequently imported into common software programs (e.g., Microsoft Excel, Matlab, etc.). Additionally, pictures from webcams in relation to the monitored structures may be embedded (Furtner et al. 2013). In order to allow users to access and review the archived and/or received data files, platforms have been developed that can present summarized information to users. According to Glisic et al. (2014), the platform is considered multifunctional as it is used for accessibility and visualization of meta-data and to configure sensors and associated reading units, extract data, set alerts, and create reports. The Main System Software (which enables the platform) communicates with the SHM system, pulls the data to a Central Server, and performs cleansing, preprocessing, and synchronization of the data (Glisic et al. 2014). Lee (2007)
describes the architecture of a platform supporting automatic generation of reports in three formats: Microsoft Excel Worksheet, PDF, and a hard copy (e.g., an option allows the users to print a hard copy of the displayed results). Each report can contain the following information: 1) monitoring period of interest, 2) event history that presents each recorded event, 3) event histogram, 4) statistical trends of events including absolute maximum and average, and 5) summary of messages regarding “alarm events” (Lee, 2007). Monitoring systems can use SHM data to trigger alarm messages or notifications which may be sent via e-mail or SMS in case of exceeding or shortfall of static or even dynamic limits, missing data input or malfunctions like interruption of power supply. The notifications may be provided with an internal priority in order to separate “warnings” or “alarms” (Ciribini et al. 2017). Furthermore, the alarm messages could include the date and time of each occurred event, sensor identification, cause of event (either overload or impact) and the magnitude of the event (Lee, 2007).

A section of the questionnaire described in this chapter was designed to evaluate perceptions of mass timber stakeholders regarding access to monitoring data. The aim of this part of the questionnaire was to recommend SHM platform functionalities enabling desired ways to access and share monitoring data for different tasks and stakeholder needs.

3.1.3 Available data visualization tools

In the last decade, efforts have been made to develop effective ways to visualize and communicate SHM data. A study by Napolitano et al. (2018) presents a new method for visualizing SHM data in 3D. This approach integrates visualization of sensor networks and data in a virtual environment, where the latter consists of a combination Virtual Tour (VT) and Informational Modelling (IM). In the VT/IM environment, a user can access raw and analyzed data, and set visualization of data relative to a structure (e.g., technical drawings) or to a SHM system (e.g., color coding of the sensors). Feedback from civil engineering students familiar with SHM was used for validation of the monitoring data visualization system. It was found that the 3D platform allowed a user to quickly familiarize themselves with the structure and the
SHM system, understand from which part of a structure the data came from, and see how results of data analysis related to the structure (Napolitano et al. 2018).

Mustapha et al. (2018) presents another monitoring data visualization system implementing two techniques: Augmented Reality (AR) and Virtual Reality (VR). Sensor data could be extracted in the AR platform using a custom Smartphone app and overlaid on the image in a smartphone display. In the VR interface, the Building Information Modeling (BIM) of a monitored project was imported into a gaming software engine. A user could select multiple sensors, graph and compare data, while walking through the building in a virtual environment. It was found that VR creates an environment for users to interact with sensors and to visually investigate both the 3D model and its corresponding data in a singular analysis ecosystem.

In a study by Glisic et al. (2014), three platforms for SHM live data accessibility and visualization are presented: “Panoramic Camera,” “Bridge Graphic View,” and “Bascule/Engineer View”, which allow remote, real-time or on-demand access to live data and their visualization. The Panoramic Camera platform contains the following features: live stream from a panoramic camera installed next to the monitored structure (a bridge) that shows global traffic conditions on the bridge, and a table with environmental conditions. The Bridge Graphic View platform allows for quick spatial assessment. The condition of the bridge can be correlated in real time with the acting loads, captured by four cameras. The Bascule/Engineer View platform contains diagrams with multiple plots each, and both dynamic and static data can be displayed. The data accessibility and visualization principles were iteratively improved and validated in collaboration with several representatives of four interested groups: building managers, operators, engineers, and academics. These four groups had different interests in monitoring data, and consequently, they had different requirements and needs for data visualization and accessibility. The managers were principally interested in information regarding overall condition of the structure. Consequently, they were not necessarily interested in accessing live data continuously, but rather on-demand, or when some issue is reported by a monitoring system. The
most important requirements of engineers were an easy access to targeted sets of historic data and their ample yet simple visualization that will allow for an efficient structural data analysis. The operators were interested mostly in continuous access to live data. The academics interests included those of the two other groups (engineers and operators). In addition, for research and teaching purposes, they needed more detailed site specific visualization.

In a research study performed by the sensor company SMT Research Ltd. GROUP (2014), the usefulness of information on sensor location and data value in 2D maps was evaluated by a qualitative study. Expert users in the domain of structural monitoring, such as structural engineers and data analysts, were asked to test the system to achieve insight into the usefulness of the visual analytics solution in a real setting. The results indicated that analysts appreciated having an overview of the spatio-temporal data and considered it efficient to be able to directly correlate temporal sensor readings with their corresponding spatial location.

De Amicis et al. (2019) discuss ways of presenting and exploring monitoring data in an immersive environment, using holographic interfaces, which project data into physical space, and display technologies, using mobile devices or helmet mounted displays. These AR/VR visual modalities are also combined with sonified data.

Sonification of data is presented by Kramer et al. (1997) as a way to transform data relations in a “perceived relation” in an acoustic signal. While visualization formats can provide an overview of large amounts of data, auditory representations can be useful to support tasks such as pattern recognition, trend analysis, data comparison and identification of anomalies and outliers (De Amicis et al. 2019; Ferguson et al. 2012). The effectiveness of visual data presentation formats is described in research by Johannessen and Fuglseth, (2014). This study contributes to the understanding of how data presentation formats may affect decision-making. It was found that decision-makers needed both tables and graphs to support their decision-processes. According to Vessey (1994), graphs are spatial presentation formats, i.e. they emphasize
relationships among the data, tables are numeric, i.e., they emphasize presentation of discrete data values. The graphic display may give an overview about the data and will increase humans’ general understanding of the relationships among variables, on the other hand, additional tables can increase detail understanding (Johannessen and Fuglseth, 2014).

The aim of the survey presented in this chapter was to investigate preferences of stakeholders regarding data visualization formats currently available on commercial SHM platforms, as well as data presentation approaches recently explored in the literature. The aim of this questionnaire was to recommend efficient data communication tools for a range of different monitoring applications.

3.1.4 Who are the SHM users
Anderson and Vesterinen (2006) identify key stakeholders of SHM projects, namely authorities, building owners and facility managers, users (e.g., building occupants, bridge users), designers, contractors, and researchers. Asset owners will likely obtain most value from a SHM system that aids in decision making related to minimize maintenance effort or maximize service life time and safety (Webb et al. 2015). Mustapha et al. (2018) highlight the value of monitoring data to inform designers, contractors and developers on future projects. Glisic et al. (2010) add to the categories of SHM data users, listed by Anderson and Vesterinen (2006), also technology providers.

A literature survey of SHM projects of timber structures covering projects from 1980 to 2019 showed that most of the documented projects were research-driven and that the primary SHM data users of most of industry-driven projects were owners of buildings (presented in the previous chapter). Building owners mostly used SHM to assess structural safety/serviceability and damage of existing and historical buildings. In these cases, the value of information provided by monitoring data is often related to the historical/cultural or infrastructural value of the structure; in many cases, SHM data provided useful information for the maintenance, repair or retrofitting of those
structures. The results of the survey also showed that all research-driven projects were aimed to evaluate a building performance and/or to validate/calibrate numerical models. In this case, information provided by monitoring data contributed to developing, confirming, or improving methods of design; allowed comparing design assumptions with the real behavior of a system; and supported experimental/laboratory studies. The survey also showed that data-informed actions were mostly taken in buildings monitored for safety/serviceability assessment purposes (presented in the previous chapter).

Fifteen SHM projects have been recently implemented in mass timber buildings featuring different types of engineered wood products (EWPs). All of these new buildings were monitored to evaluate their performance during construction and/or after commissioning (presented in the previous chapter). The main scope of these projects was to evaluate the performance of new construction techniques/systems. This information is critical in a performance-based design approach, both to designers (architects and engineers), and manufacturers who develop new systems/products (Balageas et al. 2006), (Mustapha et al. 2018). Contractors can also benefit from information provided by the monitoring data for making decisions to improve the construction plan. This information includes monitoring data of components and access to the real-time condition of the structure during construction. For instance, moisture content monitoring plans have been implemented to evaluate moisture response of CLT panels exposed during construction (Liisma et al. 2019; Mustapha et al. 2017; Schmidt et al. 2019; Wang, 2016; Zelinka et al. 2018).

Muszynski et al. (2017) discuss findings of a survey among CLT manufacturers, and the results show that nearly one-third of manufacturers were involved in building construction. Mass timber construction calls for integrated design approaches, creating a close collaboration among architects, engineers, contractors and manufacturers. As such, mass timber product manufacturers are included in the list of AEC stakeholders considered in this study.
Different data users may have differing preferences in the way monitoring data can be accessed, presented and used to support specific actions. Mustapha et al. (2018) observe that access to the real-time status of a structure during construction gives architects, engineers and contractors critical information to make informed decisions to either validate or improve the construction plan. Additionally, data recorded during the life of the building helps architects and engineers to validate the design decisions and proves the viability and feasibility of the design. Tannert et al. (2011) found that an automated remote monitoring system provides efficient data to owners of structures, who must ensure the on-going safety of their structures.

3.1.5 The context of the study
This study focused on the mass timber industry in the U.S. Pacific Northwest, due to the fact that this region has the potential and the inherent strengths to be a national competitor in mass timber markets. The forest sector is a historical industry in Oregon, and recent initiatives have made this state one of the major national hub of the mass timber industry promoting the development of advanced wood product markets (Oregon BEST, 2017). The Oregon Building Codes Division has been instrumental in getting mass timber construction permitted, thus fostering a number of public and private mass timber projects in the state (BCD, 2015). The establishment of the first certified CLT plant in the nation and the development of one of the newest engineered wood products (Massive Plywood Panels – Law, 2014) are examples of entrepreneurial initiatives which have taken place in the last years in the region.

The Tallwood Design Institute (TDI), an interdisciplinary collaborative effort of Oregon State University and the University of Oregon, provides research and educational support to professional and industry involved in mass timber construction. A series of events take place regularly in the state to exchange ideas, promote initiatives, disseminate project findings and fuel the industry momentum. The TDI MeetUp and the Mass Timber Conference (MTC) are the two main initiatives in this regard. The TDI MeetUp is an informal monthly gathering, in forms of workshops and
other continuing education and networking opportunities for building professionals interested in engineered wood products.

The Forest Business Network’s MTC was launched in 2016. The MTC attracts professionals from across the forest, manufacturing, design, development, and construction industries. This conference is the largest gathering of cross-laminated timber and other mass timber experts in North America with a special focus on manufacturing and mid- to high-rise construction (https://www.masstimberconference.com/).

3.2 Methods
A survey was conducted to investigate stakeholder perceptions of the usefulness of SHM data and to analyze their preferences on data use, access and visualization. This survey was approved by a university Institutional Review Board for research on human subjects.

3.2.1 Target population and sampling frame
The target population of this study was designers (architects, engineers), contractors and manufacturers in the U.S. Pacific Northwest mass timber industry. Given the role of the TDI and the relevance of the MTC in the target region, it was plausible to state that this study target population includes participants to TDI’s activities and to the MTC. Subscribers of the TDI newsletter are manufacturers, architects, engineers, construction professionals, developers, code officials, municipal planners, among others, (https://www.meetup.com/Critical-Mass-Timber-Meetup/). Similarly, attendees to the MTC are architects, engineers, real estate developers, construction companies, sawmills, mass timber manufacturers, academia, policymakers, code officials, students, among others. Therefore, a subgroup of subscribers of the TDI newsletter, and of attendees and exhibitors in the 2019 MTC were selected as a sampling frame.
The sampling frame was defined considering: reasonable access, and potential interest to this study topic. In this study, convenience sampling was used as a sampling method. Convenience sampling is a specific type of non-probability sampling that relies on data collection from population members who are available and willing to participate. This type of sampling method does not require that a simple random sample is generated, since the only criteria is whether the participants agree to participate (Suen et al. 2014). This type of sampling was selected because members of the target population meet certain criteria, such as easy accessibility, and the willingness to participate.

3.2.2 Questionnaire and data collection

A web based questionnaire was developed in the platform Qualtrics. The questionnaire included a total of 15 questions. Question types were; multiple choice, Likert-like, select all that apply and ranking. Questions focused on three sections: 1) demographic information, and perceptions of: 2) the applicability and usefulness of monitoring data, and 3) the accessibility and communication of monitoring data. Questions investigating perceptions of SHM usefulness and applicability were based on outcomes of a literature survey reviewing scope and application of SHM of timber structures (presented in the previous chapter). Questionnaire items in this category were generated considering factors impacting durability, safety, serviceability and performance of timber buildings. Questions investigating respondent’s preference on monitoring data format, accessibility, and visualization were generated considering functionalities currently available in commercial SHM database platforms and analytics software, as well functionalities and interfaces developed and tested in research studies reported in sections 3.1.2 and 3.1.3. This part of the questionnaire was refined after receiving expert feedback from SHM technology companies. Table 3.1 presents the list of questions, related research questions and type of analysis.
Table 3.1: list of questions, related research questions and type of analysis.

<table>
<thead>
<tr>
<th>Topic / Research question</th>
<th>Question</th>
<th>Type1</th>
<th>Data analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>-Demographic</td>
<td>-What is your occupation?</td>
<td>(S)</td>
<td>“MC” questions: The data were coded into a single variable, the numbers 1-4 used to code the data were given labels the same of choices for each question.</td>
</tr>
<tr>
<td></td>
<td>-How many years of experience do you have in this role?</td>
<td>(MC)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-How many projects have you done in the last five years?</td>
<td>(MC)</td>
<td></td>
</tr>
<tr>
<td>-What are mass timber AEC industry perceptions and awareness of the applicability and usefulness of monitoring data?</td>
<td>-Please indicate how useful you think monitoring is to support the following actions.</td>
<td>(L)</td>
<td>“L” questions: The data were coded into a single variable, the numbers 0-4 used to code the data were given labels the same of 5-points rating for each question.</td>
</tr>
<tr>
<td></td>
<td>-Please rank, from the most to the least detrimental, the following factors impacting the service life of a timber building.</td>
<td>(R)</td>
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<tr>
<td></td>
<td>-Please indicate how critical you think it is to monitor moisture content of timber in the following locations.</td>
<td>(L)</td>
<td></td>
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<tr>
<td></td>
<td>-Please indicate how critical you think it is to measure displacements in timber buildings in the following locations.</td>
<td>(L)</td>
<td></td>
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<td></td>
<td>-Please indicate how important you think it is to monitor vibration/seismic movement in the following types of buildings.</td>
<td>(L)</td>
<td></td>
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<tr>
<td></td>
<td>-What is your preferred monitoring duration?</td>
<td>(S)</td>
<td></td>
</tr>
<tr>
<td>-What are mass timber AEC industry preferences regarding access to monitoring data?</td>
<td>-What type of monitoring data would you like to access?</td>
<td>(S)</td>
<td>“S” questions: The responses were coded as 1 = Yes and 0 = No.</td>
</tr>
<tr>
<td></td>
<td>-What type of accessibility would you like to have to the monitoring platform?</td>
<td>(S)</td>
<td></td>
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<tr>
<td></td>
<td>-What type of tasks would you like to perform with the monitoring platform?</td>
<td>(L)</td>
<td></td>
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<tr>
<td></td>
<td>-Please rank, from the most to the least preferred, the format in which you would like the monitoring data to be presented.</td>
<td>(R)</td>
<td>“R” questions: The Modified Borda Count method was used to analyze ranking of ’x’ number of items.</td>
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<tr>
<td></td>
<td>-Please indicate the degree of usefulness of the following data visualization formats.</td>
<td>(L)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-How would you like to access monitoring data?</td>
<td>(S)</td>
<td></td>
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</table>

1. Question types: MC = multiple choice, L = Likert-like, R = ranking, S = select all that apply.
The questionnaire was distributed 1) in-person during the MTC, on 21 March 2019, and 2) administered online through the TDI emailing system to the subscribers of the TDI newsletter. Distribution of the questionnaire began in December 2018 and ended in March of 2019. The number of people who responded to the survey online was 12 and in-person respondents were 28.

A number of limitations in the data collection may affect the findings discussed in the following sections. Respondents were recruited online by sending an email including a recruitment letter and a link to the survey. According to the Tailored Design Method (Dillman et al. 2014), multiple rounds of emails should be sent in an online survey, with each round being sent a couple of weeks apart, to increase the possibility of obtaining more answers. However, due to the TDI restricted policy, no follow up emails were sent in this study. In-person distribution of the questionnaire was affected by the time constraint during one day of the conference (i.e., average duration of the survey was 15 minutes and participants took the survey one-by-one during the breaks between the conference sessions). As a result, findings of this study reflected only a limited sample within the target population.

It was desirable to have an equal number of respondents from each group in the sampling frame, however, it was not possible to control the distribution of participants in each category. Therefore, another limitation of the study was the uneven representation of respondents within the sample. In particular, the approach of collecting data in person may not represent equally sampling frame categories of this study, since participants were recruited based on their proximity and temporary availability. Furthermore, partial responses were not recorded due to the fact that it was not possible to accurately control the number of sent emails and recipients for the online data collection, so an exact response rate could not be calculated.
3.2.3 Data analysis

Descriptive data analysis of the questionnaire was conducted using Microsoft Excel (Microsoft 2016). Statistical analysis was conducted using the software SPSS (version 24.0, 2016). Tableau software (version 2019.1) was used for visualization of results.

The data analysis method used for each type of questions are listed in Table 3.1. The Modified Borda Count (MBC) was used to analyze responses requiring respondents to rank items in order of preference (Emerson, 2013). In this method, respondents rank ‘x’ number of items, the item they rank first receives a count of (x), the item they rank second receives a count of (x-1), the item they rank third receives a count of (x-2), and so on until the ‘x’th item receives a count of (1). Chi-Square test was utilized in SPSS to analyze Likert-like questions for each category type. This test provided a contingency table to analyze distribution of response frequency among AEC categories (Pallant, 2010).

When a research is done, particularly with human beings, it is rare that complete data will be obtained from every case. Descriptives was run in SPSS to determine what percentage of values was missing for each of the variables (Pallant, 2010). A lot of unexpected missing values were found. This was for instance due to the fact that some respondents just answered to the demographic questions and did not respond to questions related to the applicability of monitoring data. They stated that those questions were not in their field of expertise. These cases were excluded from the data analysis. As a result, 40 responses were further analyzed, some with missing data.

3.3 Results

This section described results of the survey. The results investigated respondent’s demographic information, stakeholder perceptions on the applicability and usefulness of monitoring data. The investigated results also included stakeholder perceptions on the accessibility and communication of monitoring data.
3.3.1 Demographics

The survey collected data on respondent demographics. The research investigated responses of a total of 40 respondents with different occupations including architects, engineers, and manufacturers. The results presented one respondent as a contractor. Due to the fact that the sample size of this targeted subgroup was too small, that was excluded from the results. Figure 3.1 illustrates the number of respondents with different occupations, years of experience and number of completed projects in the last five years. The completed projects included all types of projects and were not exclusively limited to mass timber buildings. As the figure depicts, of the 40 completed questionnaires, 70% (28) of respondents were designers (both engineers and architects), and 30% (12) were manufacturers. Of the 19 engineers 42% (8) had less than 5 years of experience, 42% (8) had 5-15 years of experience, just one had 16-25 years of experience, and 10% (2) had more than 25 years of experience. The first group mostly completed 1-5 projects in the last five years and the other groups mostly completed more than 10 projects, however, a few respondents (7) did not complete any project in the last five years. Of the 9 architects 33% (3) had less than 5 years of experience, 44% (4) had 5-15 years of experience, just one architect had 16-25 years of experience, and one had more than 25 years of experience. Architects with less than 5 years of experience did not complete any project in the last five years, while all the other architects completed 6 or more projects in the same timeframe.

Of the 12 responding manufacturers 17% (2) had less than 5 years of experience, 42% (5) had 5-15 years of experience, 17% (2) had 16-25 years of experience, and 25% (3) had more than 25 years of experience. The second group, which included most manufacturers, completed more than 10 projects in the last five years.
3.3.2 Perceptions on the applicability and usefulness of monitoring data

Figure 3.2 illustrates perceptions of respondents regarding the usefulness of monitoring to support decision-making processes. Respondents indicated ‘comparison of design assumptions with real behavior of a system’ as the type of action which mostly benefits from information provided by SHM data (24). Respondents also indicated ‘support experimental/laboratory studies (4)’ and ‘validate/calibrate numerical models (3)’ as the types of actions, which less benefit of SHM data.

All the respondent designers (both engineers and architects) considered using SHM data to control conditions of buildings during construction from useful (39%) to fairly useful (18%) to very useful (43%). Interestingly, the only group in which there were respondents not particularly appreciating the value of SHM to control conditions of building during construction were manufacturers (17% - slightly useful). SHM was considered very useful to detect damage after an exceptional event (such as an earthquake) (52.5%), rather than for early detection of damage during the service life of a building (32.5%). The only category that seemed to not totally agree on the usefulness of SHM data for damage detection after an exceptional event was engineers.
(5% of total engineers). Designers (both engineers and architects) considered using SHM data to validate/calibrate numerical models very useful (30% of total), however, only 17% of manufacturers found that action very useful and one manufacturer remarked that monitoring data was not at all useful to validate/calibrate numerical models.

Table 3.2 illustrates responses ranking factors impacting the service life of a timber building, from the most to the least detrimental. Respondents ranked ‘decay’, ‘fastener corrosion’, and ‘mold’ as the top most detrimental factors impacting the service life of a timber building, respectively. ‘Instability’, ‘vibrations’, ‘cracks’, ‘deflections’ were ranked as the four least detrimental factors. It is worth mentioning that ‘cracks’ and ‘deflections’ were in the same level as the total Modified Borda Count of both were equal. The table shows that the highest to the lowest number of respondents who ranked ‘instability’ as the least detrimental factor, were engineers, architects, and manufactures, respectively.
Table 3.2: Ranking of the factors impacting the service life of a timber building.

<table>
<thead>
<tr>
<th>Factors impacting the service life of a timber building</th>
<th>Occupation</th>
<th>Modified Borda Count (MBC)</th>
<th>Number of times factor was selected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decay</td>
<td>Architect</td>
<td>62</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Engineer</td>
<td>126</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>Manufacturer</td>
<td>75</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td><strong>263</strong></td>
<td><strong>39</strong></td>
</tr>
<tr>
<td>Fastener corrosion</td>
<td>Architect</td>
<td>49</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Engineer</td>
<td>120</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>Manufacturer</td>
<td>63</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td><strong>232</strong></td>
<td><strong>39</strong></td>
</tr>
<tr>
<td>Mold</td>
<td>Architect</td>
<td>54</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Engineer</td>
<td>115</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>Manufacturer</td>
<td>62</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td><strong>231</strong></td>
<td><strong>39</strong></td>
</tr>
<tr>
<td>Damage to connections</td>
<td>Architect</td>
<td>48</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Engineer</td>
<td>96</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>Manufacturer</td>
<td>55</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td><strong>199</strong></td>
<td><strong>39</strong></td>
</tr>
<tr>
<td>Dimensional changes</td>
<td>Architect</td>
<td>31</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Engineer</td>
<td>83</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>Manufacturer</td>
<td>70</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td><strong>184</strong></td>
<td><strong>39</strong></td>
</tr>
<tr>
<td>Cracks</td>
<td>Architect</td>
<td>34</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Engineer</td>
<td>89</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>Manufacturer</td>
<td>51</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td><strong>174</strong></td>
<td><strong>39</strong></td>
</tr>
<tr>
<td>Deflections</td>
<td>Architect</td>
<td>36</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Engineer</td>
<td>94</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>Manufacturer</td>
<td>44</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td><strong>174</strong></td>
<td><strong>39</strong></td>
</tr>
<tr>
<td>Vibrations</td>
<td>Architect</td>
<td>44</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Engineer</td>
<td>67</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>Manufacturer</td>
<td>43</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td><strong>154</strong></td>
<td><strong>39</strong></td>
</tr>
<tr>
<td>Instability</td>
<td>Architect</td>
<td>47</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Engineer</td>
<td>65</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>Manufacturer</td>
<td>32</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td><strong>144</strong></td>
<td><strong>39</strong></td>
</tr>
</tbody>
</table>

Figure 3.3 presents perceptions of respondents related to the criticality level of monitoring wood moisture content in different locations. The results showed that the most critical locations to monitor moisture content were ‘roof assemblies’ and ‘skylight...
connections’ (40% and 39% of total, respectively), and the least critical location to monitor moisture content was in ‘CLT panels during transport and storage’. It is worth mentioning that two respondents (one engineer and one manufacturer) indicated that monitoring of moisture content of ‘CLT panels during transport and storage’ was not at all critical. Additionally, just one architect indicated the same for locations ‘close to structural connections/joints’.

Respondents indicated as the second very critical location to monitor moisture content ‘skylight connections’, which was selected by 11 designers and 4 manufacturers. Moisture monitoring of ‘Façade assemblies’ was considered just slightly critical by 41% of the designers and 27% of the manufacturers.

![Figure 3.3: Respondent perceptions on critical locations to monitor moisture content of timber.](image)

Figure 3.3 shows perceptions of respondents related to the criticality level of measuring displacements of timber members in different locations in a building. As the graph shows, 'beam to column connections' were considered as the most critical locations (22.5% of total), and 'wall to wall connections (differential movements)' were
considered as the least critical locations to measure displacements (43% of total respondents considered either slightly or not at all critical).

‘Columns’, 'floors' and 'roofs' were considered very critical locations to monitor displacements by designers (26%, 22% and 26% of total designers for each location, respectively). It is worth mentioning that all listed locations were considered worth monitoring by engineers. The highest percentage of manufacturers did not agree on the criticality of measuring displacements for locations in ‘walls’, 'wall to floor connections', and 'wall to wall connections' (33% of total manufacturers for each considered these locations either slightly or not at all critical).

![Graph showing respondent perceptions regarding critical locations to measure displacements.](image)

*Locations were ordered from the most to the least criticality (Total responses)*

**Figure 3.4:** Respondent perceptions regarding critical locations to measure displacements.

**Figure 3.5** illustrates perceptions of respondents related to monitoring of vibration/seismic movement in different types of buildings. As the results showed, timber buildings used for critical infrastructures (hospitals, etc.) were indicated as the most important type of buildings to monitor vibration/seismic movement (from important to very important by 88% of total respondents). However, some respondents (two manufacturers and one engineer) considered dynamic monitoring of this type of buildings slightly or not at all important. The graph shows that large-span timber
structures were considered as the least important type of buildings to monitor vibration/seismic movement (12.5% of total indicated either slightly or not at all critical). All the respondents (designers and manufacturers) indicated monitoring of vibration/seismic movement in mass timber buildings in seismic areas from important (27.5%) to fairly (22.5%) to very important (40%). Interestingly, the only group who did not fully agree on the importance of dynamic monitoring of mass timber buildings in seismic areas was manufacturers (17% of responding manufacturers). Nineteen designers considered very important to monitor dynamic behavior of tall wood buildings, while manufacturers were more in disagreement on the importance of this task (just one manufacturer considered it very important, 7 either important or fairly important, and 3 slightly or not at all important). Bridges were considered as the second most important type of structure to monitor vibration and seismic movements, by 17 designers and four manufacturers.

Figure 3.5: Respondent perceptions related to monitoring of vibration/seismic movement in different types of buildings.

Figure 3.6 presents respondent’s preferences related to monitoring duration. The chart shows that monitoring of timber buildings during the entire service life of a building was considered as the most preferred duration by 65% of respondents. These respondents included 18 designers, and six manufacturers. Monitoring a building during construction was the second most preferred duration of a monitoring project by designers (38% of total) and manufacturers (13.5% of total). Monitoring of timber
buildings for a duration of just five years was the least preferred duration (19% of total respondents).

![Preferred monitoring duration chart]

Figure 3.6: Preferences of respondents related to monitoring duration of timber buildings (monitoring durations were ordered from the most to the least preferred).

3.3.3 Perceptions on the accessibility and communication of monitoring data

Figure 3.7 illustrates respondent preferences regarding the type of monitoring data which they liked to access. The results showed that historic data and statistics were considered as the most preferred type of data to access (81% and 72% of total responses, respectively). Historic data were preferred by 94% of engineers, 78% of architects and 60% of manufacturers. Statistics were preferred by most of manufacturers (90%) and then by 78% of architects and 59% of engineers, respectively. Real-time data were of less interest for the respondent stakeholders, if they are not associated to a dynamic demand (i.e., real time on demand 36% of total responses). Raw data and alarm data were the least preferred type of accessible data (28% and 17% of total responses, respectively). In particular, none of the respondent architects expressed interest in accessing raw data. Access to pre-processed data (after correction/filtering) was less attractive than access to post-processed data (i.e., statistics over a certain period), with 61% and 72% total preferences, respectively. It is worth mentioning that the only difference between the number of respondent categories who
would like to access to post-processed and pre-processed data was for manufactures (9 and 5 for each, respectively).

![Figure 3.7: Preferences of respondents regarding the type of monitoring data to access.](image)

Figure 3.8 shows respondent preferences regarding the type of accessibility to the monitoring platform. As the results show, the possibility to create reports and compare data or benchmark results with different projects were two of the most desired functionalities of a SHM platform across the three groups of respondents. However, 67% of engineers considered as the most valuable function, the possibility to download data. Manufacturers mostly liked the possibility to ‘combine data from different sensors’ and ‘create reports’ (60% of total manufacturers for each). In addition to 'compare data or benchmark results with different projects', the possibility to create reports was also preferred by most of architects (78% of architects for each). Sensor and unit configuration was considered the least valued function by the three groups of respondents (9 of total count), followed by setting alerts (13 of total count). Access to the monitoring platform for data sampling was less attractive than access to data filtering, with 43% and 49% total preferences, respectively.
Figure 3.8: Respondent preferences regarding the type of accessibility to the monitoring platform.

Figure 3.9 presents respondent preferences regarding the type of tasks to perform with the monitoring platform. Correlation tasks resulted among the most desired tasks across different groups of respondents. In particular, the possibility of correlating sensor data with weather patterns at a specific date and the possibility of correlating a measured value and the corresponding sensor location were both desirable tasks for all the respondents. Comparison tasks, allowing to compare measured values for attributes in spatial or temporal intervals were the less desirable type of tasks. In particular comparing readings from different sensors based on specific spatial information (‘What sensors are located on the same elevation’) was the least desirable option.

Among the proposed identification tasks (i.e., the search for the occurrence of all specific values, trends, anomalies, and extremes for attributes at specific locations and points of time), ‘reporting the maximum/minimum value of a specific sensor’ was indicated as the most desirable task. Twenty-six respondents, including 16 engineers, six architects and four manufacturers found this task either very desirable or desirable.

Trend identification (‘What is the trend for the sensor’s values?’) was considered as the least desirable task among other identification tasks.

Specific spatial information, comparing readings from different sensors (‘What sensors are located on the same elevation?’) was however the least desirable task to perform.
Figure 3.9: Respondents preferences regarding the type of tasks to perform with the monitoring platform.

Table 3.3 illustrates responses ranking preferred formats for the presentation of monitoring data. Respondents ranked ‘visual (graphics)’ and ‘text + visual’ as the top two most preferred formats (32% and 26% of total responses, respectively). Visual presentation modes were preferred by 28% of engineers, 33% of architects and 36% of manufacturers. ‘Text + visual’ was preferred by most of engineers (33%) and then by architects (22%) and manufacturers (18%).

As the table shows, ‘audible’ and ‘text + audible’ were considered as the least preferred presentation modes. ‘Audible’ presentation was the least preferred format; the highest to the lowest number of respondents who chose ‘audible’, was engineers, manufacturers, and architects, respectively.
Table 3.3: Ranking of formats of monitoring data presentation.

<table>
<thead>
<tr>
<th>Format of monitoring data presentation</th>
<th>Occupation</th>
<th>Modified Borda Count (MBC)</th>
<th>Number of times factor was selected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual (graphics)</td>
<td>Architect</td>
<td>53</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Engineer</td>
<td>93</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>Manufacturer</td>
<td>61</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td><strong>207</strong></td>
<td>38</td>
</tr>
<tr>
<td>Text + visual</td>
<td>Architect</td>
<td>45</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Engineer</td>
<td>99</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>Manufacturer</td>
<td>50</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td><strong>194</strong></td>
<td>38</td>
</tr>
<tr>
<td>Text (reports, articles)</td>
<td>Architect</td>
<td>39</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Engineer</td>
<td>90</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>Manufacturer</td>
<td>60</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td><strong>189</strong></td>
<td>38</td>
</tr>
<tr>
<td>Text + Visual + audible</td>
<td>Architect</td>
<td>40</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Engineer</td>
<td>59</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>Manufacturer</td>
<td>31</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td><strong>130</strong></td>
<td>38</td>
</tr>
<tr>
<td>Visual + audible</td>
<td>Architect</td>
<td>31</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Engineer</td>
<td>56</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>Manufacturer</td>
<td>29</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td><strong>116</strong></td>
<td>38</td>
</tr>
<tr>
<td>Text + audible</td>
<td>Architect</td>
<td>21</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Engineer</td>
<td>48</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>Manufacturer</td>
<td>44</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td><strong>113</strong></td>
<td>38</td>
</tr>
<tr>
<td>Audible (alarms, sounds, verbal notification)</td>
<td>Architect</td>
<td>23</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Engineer</td>
<td>53</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>Manufacturer</td>
<td>33</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td><strong>109</strong></td>
<td>38</td>
</tr>
</tbody>
</table>

Figure 3.10 shows respondent preferences regarding the usefulness of data visualization formats. It can be noticed that not all respondents agreed on the usefulness of many of the proposed visualization formats. It appears that most respondents, and especially engineers, preferred tables over graphic formats. It is worth mentioning that all engineers (100%) and 90% of manufacturers considered tables very useful and/or useful. Architects however, showed interest in advanced graphical formats, such as holographic projections into the monitored space and virtual reality. It can be remarked that all architects found holographic projections into the monitored space very useful.
and useful (100% of total architects). Seventy-eight percent of them considered virtual reality very useful or useful data visualization format.

Augmented reality (AR) was considered of less value for engineers (not at all useful 17% and rarely useful 72% of total engineers) and for manufacturers (not at all useful 10% and rarely useful 60% of total manufacturers). AR systems, displaying data overlaid onto a camera image was considered in general as the least preferred data visualization format.

Figure 3.10: Perceptions of respondents regarding the usefulness of the data visualization formats.

Figure 3.11 shows respondents’ preferences regarding the type of access to monitoring data. As the results indicated, most of respondents in each category and in total preferred to access to monitoring data from a website (81% of total). These respondents included 35% of engineers, 22% of architects and 24% of manufacturers. The results also showed that accessing monitoring data from a hardcopy report was the least preferred type of access (35% of total). Respondents mostly liked to access to monitoring data from the sensor location through a mobile device rather than a central dashboard when they were on-site (62% and 57% of total, respectively). Online access from a registered account was preferred by 41% of respondents, and least liked by architects.
3.4 Discussions

Controlling damage after a major event, such as an earthquake, and comparing design assumptions with measured performance of a building were considered the most useful applications of SHM of timber buildings by this study’s respondents. This result could be attributed to the region where the survey was conducted, the U. S. Pacific Northwest which is a high seismic area (Frankel et al. 2014). According to experiences of Kijewski-Correa and Kareem, (2007), stakeholder confidence in SHM technologies varies greatly, depending on the hazard zone (e.g., raising concerns due to earthquakes). In seismic areas, where safety and damage identification are higher priorities than serviceability/habitability limit states, owners are more motivated to invest in monitoring infrastructures. Additionally, damage detection and performance evaluation, both perceived as actions mostly benefitting of information provided by SHM data, are complementary to each other for the analysis of the seismic behavior of a building (Morris et al. 2011). Consistently to these results, vibrations were considered the most critical parameter to measure in a timber building. Regarding the types of building to monitor, respondents considered dynamic monitoring of mass timber buildings in seismic areas less important than monitoring of bridges and tall wood
buildings. Bridges were indicated as the second most important type of structure to monitor vibration/seismic movement, after “critical infrastructures, such as hospitals”. This was not unanticipated, as official SHM documents were first issued to monitor this type of infrastructure (e.g., ISIS Canada, 2002; Aktan et al. 2003). Bridges need to be monitored to avoid exceeding ultimate limit states (e.g., deformations, etc.) over time and plan their service life, which is a critical task for these type of structures to support their maintenance (as discussed in the previous chapter). Additionally, respondent’s perceptions may be attributed to the following facts. In some states of the United States, because of the high risk associated with earthquake damage, seismic monitoring is compulsory for public and critical infrastructures. For instance, according to the California Strong Motion Instrumentation Program, hospitals and bridges are the two categories of buildings that have been prioritized for seismic monitoring (California Strong Motion Instrumentation Program, last accessed in 2019). Respondents indicated the importance of monitoring of bridges, regardless of the span covered. In fact, less importance was attributed to monitoring large span timber structures in general.

The survey results also showed that SHM were considered more useful to detect damage after an exceptional event than to early detect damage during the service life of a building. Despite being vibrations the perceived most critical measurand, in particular to evaluate damage and performance after a seismic event, vibrations were not considered the most critical factors affecting the service life of a building. Other factors, such as decay and corrosion were perceived as the most impactful on a timber building service life. These critical factors are triggered by specific environmental and material conditions, such as high relative humidity, and high or fluctuating wood moisture contents. In related studies (Markström et al. 2018; O’Connor et al. 2004), decay was mentioned as the top category among wood product disadvantages or weaknesses. In a study by Conroy et al. (2018) architects in the U.S. West coast indicated decay/durability as the biggest weakness of wood products. This can be traced back to wood’s organic nature, which makes it more susceptible to biotic decay (Zabel and Morrell, 1992). In another study, among the most used EWPs in mass timber
buildings, CLT was indicated as low-performing in post construction maintenance (Laguarda Mallo and Espinoza, 2015). A research by Schmidt et al. (2018) indicates that CLT dries at a slower rate than it wets. The threat of decay in mass timber buildings due to environmental factors such as rain exposure, temperature, high humidity makes characterizing the hygrothermal conditions important for safe implementation and utilization of timber structural products (Alsayegh, 2012; Kordziel, 2018). Short-term wetting of mass timber elements or poorly controlled high humidity conditions will ultimately lead to mold development. Wood that remains wet (>20% MC on the surface) for any extended period is likely to be colonized by fungi. Mold occurs when ambient RH ranges between 80% and 95%. Mold is also an excellent indicator of a moisture problem that may ultimately lead to decay. An MC above around 26% and the presence of otherwise favorable conditions are generally required for decay initiation (Wang et al. 2018; Viitanen et al. 2010). According to the literature survey on SHM projects of timber structures presented in the previous chapter, hygrothermal behavior/durability phenomena have been mainly investigated within the scope of service life planning of timber structures. Service life planning is a critical task to inform maintenance. Thus, monitoring of mass timber buildings to plan their service life could be an effective way to control decay, and contribute to removing a barrier for their adoption.

The results showed that respondents indicated as the most critical location to monitor moisture content ‘roof assemblies’. This could be justified by the fact that roof assemblies are the parts of a building envelope which more directly experience precipitation conditions (Kordziel, 2018) and therefore could be prone to leaking (Dietsch et al. 2015). It is worth mentioning that while roof leakage can be a consequence of erroneous installation or poor maintenance, a recent study pointed to facades as vulnerable parts of mid- and high-rise timber building enclosures to moisture ingress due to precipitation, due to the effect of wind-driven rain on the upper stories and increased run-down water at the lower floors (Ott et al. 2015).

Respondents indicated ‘CLT panels during transport and storage’ the least critical location to monitor moisture content. This can be traced back to the perception that
timber panels remain dry during the shipping phase, and monitoring of moisture content is therefore less critical. The limited concern of risks associated to moisture exposure during transport and storage is confirmed by findings of a research by Zelinka et al. (2018) describing the hygrothermal performance of CLT and glulam members during transportation and construction of Carbon 12, an 8-storey timber building in Portland, OR.

Respondent preferences for a monitoring project duration leaned towards either a very long duration (i.e., the entire service life of a building) or a short duration but with an early start (second most preferred duration was during construction). These results may suggest to start monitoring during construction and continue it for the entire service life. This expectation requires a very robust SHM system and a SHM platform capable of managing large-scale datasets and provide necessary access to them. Dealing with big data is considered in fact by many authors as one of the most prominent challenges of SHM systems (Cremona, 2016). Consequently, there is a need for communication of data through carefully designed interfaces to produce value to its stakeholders. Accuracy in big data may lead to more confident decision making, and better decisions can result in greater operational efficiency, cost reduction and reduced risk (Cremona, 2016).

The results of the survey also showed that historic data was considered as the most preferred type of data to access by respondents and mostly preferred by engineers. This result was confirmed by a research by Glisic et al. (2014), which found that the most important requirements of a SHM system for engineers were an easy access to targeted sets of historic data and their simple visualization that would allow for an efficient data analysis and evaluation of a structure's safety and performance (Glisic et al. 2014). Correlation tasks were indicated as the most desired type of tasks to perform with a SHM platform. While identification and comparison tasks can be automatized relatively easily (SMT Research Ltd. GROUP, 2014), correlation tasks firstly need to develop models that can correlate two or more parameters. Identification tasks are focused on searching for occurrences of a particular value, trend, anomaly, or
extremum and locating it in spatial and temporal datasets (e.g., identify the value of a particular temperature sensor over the set threshold). Comparison tasks compare values or trends in different spatial regions and in different temporal intervals across a subset of objects (e.g., compare the value of a particular sensor in dry conditions versus wet conditions). On the other hand, correlation tasks require measurement of multiple parameters and model updating which consists in finding the numerical models that best fit physical responses obtained from the sensors. These tasks usually require engineering judgment for choosing which structural parameters should be analyzed (Santos, 2014). Actually, SHM data can be used to develop models, which could be used to support correlation tasks. For instance, establishing models for normalizing changes related to environmental and operational effects (Cremona, 2016).

Regarding the type of visualization formats preferred by the respondents, tables and graphs were the first and second most preferred formats, respectively. A research by Johannessen and Fuglseth, (2014) also found that their study subjects (students) needed both tables and graphs to support their decision-processes. In the cited study, when respondents were asked to make decision based on their understanding of the tasks through different data presentation formats, it was found that tables facilitated the subjects’ calculations, while graphs gave overviews of trends in the data (Johannessen and Fuglseth, 2014).

While some major sensor companies have been investing on AR systems for construction management tasks and monitoring data visualization (for instance, https://mixedreality.trimble.com/), respondents of this survey were less interested in AR through mobile devices, and more interested in immersive forms of augmentation (i.e., data projected as holograms on the monitored surfaces).

3.5 Conclusions
The aim of the survey presented in this chapter was to analyze perceptions of a group of mass timber stakeholders on the applicability and usefulness of SHM data. The specific characteristics of the study setting, in particular the fact that the Pacific
Northwest is a seismic region, may have partly influenced the results, which all converge towards a higher interest for data characterizing timber building seismic behavior, in particular dynamic data.

In the last decade, there has been a clear increase in the number of multistorey timber buildings monitored to validate/calibrate numerical models, using dynamic data (as presented in the previous chapter). Given the interest of academia and industry in similar applications of SHM data, interaction between those who produce and analyze the data (mainly researchers) and decision-makers is critical to ensure that SHM systems are fully exploited.

The survey also investigated which features of the currently available SHM platforms and data visualization tools were considered useful by the AEC users. The results of this survey can be used to develop effective data communication tools and strategies allowing for data-supported decision making for the design of new structures and the service life management of built facilities.

Respondents of the survey ranked ‘visual (graphics)’ as the most preferred format for the presentation of monitoring data. This was not surprising as the literature mostly emphasizes use of visual graphs as data communication modality. Survey results on industry’s preferences on visual data representations and interest on novel visualization formats (e.g., holographic data projections) may suggest to SHM technology experts strategies to improve typical graphic formats and implement new approaches for data communication.

A limitation of the SHM projects is the potential gap between accessibility/visualization of data and consequent decision-making (e.g., by the building owner, the designer, etc.). The proper accessibility and visualization of data is crucial for the success of SHM. Inappropriate access to monitoring data can result in numerous inefficiencies, which greatly limit the value and utility of a SHM system.
Results of this survey were limited to perceptions of wood construction stakeholders in the Pacific Northwest. Moreover, findings of this study reflected only a limited sample within the target population. In future work this study could be extended to a larger population of targeted stakeholders.

References


http://tallwoodinstitute.org/

https://www.masstimberconference.com/


https://mixedreality.trimble.com/
4 OVERALL DISCUSSION AND CONCLUSIONS

The main objective of this research was to investigate the current use of structural health monitoring (SHM) data by the wood construction industry to understand how monitoring data supports decision-making processes. Another aim of this research was to understand which features of the currently available SHM platforms and data visualization tools were considered useful by the AEC users for a range of different monitoring applications. As outlined in the previous chapters, literature stated the potential of SHM data to inform decision-making processes of key stakeholders in the AEC industry. This study continued this line of research to address to what extent the information embedded in SHM data has been exploited by stakeholders in the wood construction industry. To meet these objectives, this research focused on a literature survey on SHM of timber buildings in a variety of countries and an online survey with a group of mass timber stakeholders located in the U.S. Pacific Northwest.

The study presented in Chapter 2 provided important findings highlighting the ways monitoring of timber structures has been implemented. Results of the literature review showed that there is a remarkable increase in the number of monitoring projects undertaken in the last decade, with a relatively recent shift from Europe (mostly of existing buildings) to North America (mostly of new buildings). This positive trend can be expected to continue in the future. This is likely due to the technological advancement of sensors, monitoring equipment and the wood industry. The survey results also showed that most of the multistorey buildings were monitored to validate/calibrate numerical models. As applicability of laboratory data for predicting the behavior of an actual structure is limited, SHM data is fundamental to accounting for long-term effects and changes in climate conditions. Literature review of SHM of timber buildings showed that data-based actions were mostly taken in buildings monitored for safety/serviceability assessment purpose. The research also investigated who the primary users of SHM data were, and two main categories of data users were identified as owners and researchers. The information provided by the SHM data related to the historical/cultural or infrastructural structures is often used by owners of
buildings for the maintenance, repair or retrofitting of those structures. Additionally, the information provided by the SHM data related to the new buildings is often used by researchers for developing, confirming, or improving methods of design; comparing design assumptions with the real behavior of a system; and supporting experimental/laboratory studies. Therefore, identifying the main scopes and applications of SHM is critical for maintaining expected performance levels of a timber structure during its service life and supporting decision-making. The results of this literature survey can be used to develop strategies allowing for data-supported decision-making for the preservation of historic buildings, the design of new structures, and the service life planning of built facilities.

The study in Chapter 3 evaluated the perceptions of a group of mass timber stakeholders on the value of SHM data, preferences for ways to access and visualize monitoring data. The results of the study showed that most respondents have a higher interest in data characterizing timber building seismic behavior, in particular dynamic data. Their perceptions could be attributed to the seismicity of the U.S. Pacific Northwest. Findings of the chapter also indicated that most respondents considered comparing designed with measured performance of a building as the most useful SHM application. According to findings of Chapter 2, there has been a clear increase in the number of timber buildings monitored to validate/calibrate numerical models and accelerations were the related measured parameters. Outcomes of the study were consistent with findings of the literature survey since both researchers and industry people were mostly interested in considering dynamic behavior of timber buildings. A common interest of academia and industry in similar applications of SHM data is instrumental for full exploitation of SHM systems.

The responding industry still perceived ‘decay’, ‘fastener corrosion’, and ‘mold’ as the most detrimental factors, which shows that these concerns, also expressed in previous studies, have not been sufficiently addressed so far (e.g., Markström et al. 2018; Zelinka et al. 2014; Wang et al. 2018). A majority of respondents reported ‘decay’ as the most detrimental factor impacting the service life of a timber building. According
to findings of Chapter 2, monitoring of mass timber buildings to plan their service life could be an effective way to control decay, and contribute to removing a barrier for its adoption.

Responding industry, and especially engineers, are mainly interested in access to historic data. This result is consistent with Glisic et al. (2014), who found that the most important requirements of a SHM system for engineers as easy access to targeted sets of historic data. Industry’s preferences on visual data representations and interest on novel visualization formats (e.g., holographic data projections) may suggest to SHM technology experts strategies to improve typical graphic formats and implement new approaches for data communication.

4.1 Limitations
The final database of the literature survey was limited to articles written within a timespan from 1988 to 2019 and published in English. Despite efforts of reaching saturation in the literature search, some papers may have been omitted in this survey. Literature searches were used to find relevant articles based on their titles using the word “monitoring” combined with one or more other search keywords as search words. Despite the efforts to ensure that all relevant articles were included, some papers may have been dropped in the literature survey. The literature survey also reported published SHM projects and some timber structures may have been monitored by and for non-research entities and were not documented in publications. This could explain why there was a predominance of research-driven projects from the literature survey. Industry-driven projects were less presumably documented in scientific papers or other publications.

Results of the survey on understanding perceptions of stakeholders on the value of SHM data were limited to a small group of wood construction stakeholders in the Pacific Northwest. Therefore, findings of this study reflected only a very limited sample within the target population. In future work, this study could be extended to a larger population of targeted stakeholders from different regions. As the results of the
survey presented one respondent as a contractor, in future studies, in addition to achieve a larger population of stakeholders, a better representation of the different AEC players could be achieved.

4.2 Recommendations and a proposal for future research

The results of this research, should continue to be updated as new efforts are made to develop effective ways to visualize and communicate SHM data. Consequently, the most important, “should-implement” principles could be implemented in the platform for configuration parameters accessibility and visualization along with some of the “by preference” principles (Glisic et al. 2014). Future research could replicate this study in more regions in the United States or Canada, or other areas and it would also be of interest to compare respondents across regions.

Future research could be conducted to investigate industry-driven projects for a targeted scope of monitoring or type of building, how industry derives information from SHM data visualized using different formats and how they take action using this information. The results presented in Chapter 3 showed that respondents were mostly interested in visual formats to access monitoring data, however, they did not prefer graphs as their favorite data visualization format. The results indicated that a type of graphs (scatter plots) was the second preference of most respondents, while another type of graphs (bar charts) was their less preferred data visualization format.

Since graphs have been the most common way of presenting data by most of the monitoring platforms, future research should investigate SHM graph data sense-making and use of SHM graph data to inform decisions. Shah and Hoeffner, (2002) review the cognitive literature on how viewers comprehended graphs and the factors that influence viewers’ interpretations. Three major factors were considered: the visual characteristics of a graph (e.g., format, color, use of legend, size, etc.), a viewer’s knowledge about graphs, and a viewer’s knowledge and expectations about the content of the data in a graph. These factors could be considered in a future study investigating sense-making of SHM data.
In this regard, a preliminary survey was designed during this thesis work with the aim of exploring ways to test effectiveness of SHM data presentation formats (graphs) to support decision-making. The survey presented in Appendix B, was designed to provide a tool to investigate:

1) To what extent SHM data reaches the intended audience;
2) How respondents are able to make decisions (for actions such as inspection, maintenance, repair, etc.) after evaluating typical monitoring data.

Questions were designed in two different versions: with and without scaffoldings. Scaffolding is a term referring to the guiding help of a more capable user, particularly where a user is close to performing a task independently (Suter, 2012). In the questions designed with scaffoldings, visual aids or additional information were presented along with the plotted data to guide respondents and to support understanding and interpretation of the presented data. The survey also included timing questions which were hidden questions to track the time a respondent spent on a specific question. The survey presented two SHM scenarios, showing hygrothermal monitoring data (i.e., wood moisture content data), and structural monitoring data (i.e., displacements). Questions were formulated to evaluate: 1) how SHM data were interpreted, and 2) how SHM data were used to make decisions.

Schmidt et al. (2018) state that the majority of literature does not thoroughly discuss irregularity in MC readings and commonly the raw data are presented. In order to scaffold comprehension of the MC graph of the survey, the MC data were post processed by including some techniques such as the use of superimposed moving averages and a line to define a threshold at a common MC value (>20% MC) close to the fiber saturation point of many wooden species, and to which wood is likely susceptible to be colonized by fungi (Zabel and Morrell, 1992). In order to scaffold comprehension of the displacements graph, a table published by Mustapha et al. (2018), was used along with the graph to present column shrinkage estimate calculation. Additionally, the initial position of the column was shown at zero point on the graph
and the direction of the vertical shortening and elongation of the column were shown by using arrows. Both graph and table were used to present data, since the graph showed the relationships among variables, and the additional table increased the detail understanding of discrete data values (Johannessen and Fuglseth, 2014).

Preliminary data collection was done with a limited number of two groups of respondents, undergraduate students on one hand, and wood science and engineering faculty and research assistants, on the other hand. These two groups represented two target populations: non-expert and expert SHM data users, respectively. Reingold et al. (2001) suggest that there are effects of knowledge among experts and non-experts on interpreting visual displays and extracting different information from these displays. Extensive knowledge of experts affects what they notice and how they interpret information from data (Canham and Hegarty, 2010). People who have developed expertise in particular areas (e.g., engineering, wood products and systems, mass timber construction or SHM) are able to think effectively about issues in those areas (Ericsson and Smith, 1991). Ericsson and Smith, (1991) show that important characteristics of expert's higher performance are acquired through knowledge and experience. Therefore, in this research, the highest completed degree of respondents and years of their work experience were considered to distinguish experts from non-experts people. For instance, respondents who were engineers and had experience more than five years, respondents who completed master's and doctorate degree were all considered as experts. Undergraduate students were considered as non-expert respondents. While the design of this survey is presented in this thesis, further data analysis will be done in a future work. Data collected with the proposed survey can be used to evaluate: 1) usefulness of format types to help users derive information from data; 2) usefulness of scaffolding techniques to support understanding and interpretation of the presented data.

For this purpose, response accuracy will be evaluated for each response. Correlations between time and accuracy measured for each response will be analyzed (for the two versions of the survey). Results of the two versions of the survey (questions with and
without scaffoldings) will be compared with each other to evaluate effectiveness of scaffoldings.

The proposed survey was conceived as an initial step towards a more comprehensive study investigating different types of visualization formats and scaffolding techniques. Looking forward, respondents in the U.S. Pacific Northwest showed an interest in novel visualization formats (e.g., holographic data projections), as presented in Chapter 3 of this thesis. Sensor companies could potentially benefit from collaborating with companies investing on those type of visualization tools to make their products work in conjunction with monitoring data visualization tools. Additionally, as another conception for the future research, a collaboration between researchers and experts in virtual reality and visualization tools could be performed in order to expand this study. Experts could benefit from findings of researchers in order to improve visualization tools (e.g., adding some scaffolding techniques to the plotted data).

References


APPENDIX
APPENDIX A – “SURVEY I” INSTRUMENT

Default Question Block

Hello, thank you for helping us with our study.
Below are some things about this survey that you should know

You are being asked to participate in a research project about “Communication of monitoring data of mass timber buildings to the AEC (Architects, Engineers and Construction) industry.”

The people responsible for this research are:

Mariapaola Riggo, Assistant Professor
Monvand Dilmaghani, Graduate Student,

The purpose of this study is to evaluate the preferences of the AEC industry regarding access to monitoring data and relevant information from structural health monitoring projects, and develop recommendations for implementation of effective communication tools in SHM visualization systems.

As part of the study, I would like to ask you to respond to a short survey. The questionnaire includes a total of 15 questions. This should take approximately 16 minutes for you to complete. The questionnaire will be presented online through the platform Qualtrics and you will be able to respond to the questions either using a smartphone, a tablet, and a computer which will collect your responses anonymously. You can access the platform Qualtrics through the following link: https://bit.ly/2zEIkku

You will not necessarily benefit from being in this study. There are no foreseeable risks to your involvement in this study.

Your participation is totally voluntary and you can skip questions or stop at any time. This survey is anonymous. No one will be able to identify you or your answers, and no one will know whether or not you participated in the study.

The information collected for this research will be analyzed and used as a part of a Master thesis work and for future publications/conference presentations.

If you have any questions or concerns about this study you can contact Mariapaola Riggo (mariaipaola.riggo@oregonstate.edu), 541-737-2130 or the Oregon State University Institutional Review Board (IRB) Human Protections Administration at 541-737-6005 or by email at IRB@oregonstate.edu.

If you agree to continue, please respond “next” to the beginning question of the survey and go to the next page to start the survey.
If you do not wish to continue, please respond “no” to this question and close the window.

1. What is your occupation? (select all that apply)
- Architect
- Engineer
- Contractor
- Developer
- Other

☐ Yes
☐ No
2. How many years of experience do you have in this role?

- Less than 5 years
- 5-15 years
- 16-25 years
- More than 25 years

3. How many projects have you done in the last five years?

- None
- 1-5
- 6-10
- More than 10

4. Please indicate how useful you think monitoring is to support the following actions:

<table>
<thead>
<tr>
<th>Action</th>
<th>Not at all useful</th>
<th>Slightly useful</th>
<th>Useful</th>
<th>Fairly useful</th>
<th>Very useful</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control conditions of a building during construction</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Early damage detection for building maintenance</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Damage evaluation after exceptional events (earthquakes, floods, etc.)</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Evaluation of intervention effectiveness (repair, restoration, and reinforcement)</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Comparison of design assumptions with real behaviour of a system</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Validate/calibrate numerical models</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Support experimental/laboratory studies</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
</tbody>
</table>
5. Please rank, from the most to the least detrimental, the following factors impacting the service-life of a timber building:
(To do this, drag and drop the factors and rank them)

- Mold
- Decay
- Fastener corrosion
- Dimensional changes
- Cracks
- Deflections
- Vibrations
- Damage to connections
- Instability

6. Please indicate how critical you think it is to monitor moisture content of timber in the following locations:
### 7. Please indicate how critical you think it is to measure displacements in timber buildings in the following locations:

<table>
<thead>
<tr>
<th>Location</th>
<th>Not at all critical</th>
<th>Slightly critical</th>
<th>Critical</th>
<th>Fairly Critical</th>
<th>Very Critical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floors (deflections)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roofs (deflections)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Walls (vertical movements)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Columns (vertical movements)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wall to floor connections (differential movements)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wall to wall connections (differential movements)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Foundation to wall connections</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Floor to beam connections</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam to column connections</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
8. Please indicate how important you think it is to monitor vibration/seismic movement in the following types of buildings:

<table>
<thead>
<tr>
<th>Type of Building</th>
<th>Not at all important</th>
<th>Slightly important</th>
<th>Important</th>
<th>Fairly important</th>
<th>Very important</th>
</tr>
</thead>
<tbody>
<tr>
<td>In mass timber buildings in seismic areas</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>In tall wood buildings</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>In large-span timber structures</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>In timber buildings used for critical infrastructures (hospitals, etc.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>In bridges</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

9. What type of monitoring data would you like to access? (select all that apply)
- Real-time data on demand
- Real-time data after a dynamic event (earthquake, strong wind, etc.)
- Historic data
- Raw data
- Processed data (after correction/filtering)
- Statistics (over certain periods)
- Alarm data

10. What type of accessibility would you like to have to the monitoring platform? (select all that apply)
- Configure sensors and associated reading units
- Extract data (download)
- Combine data from different sensors
- Sampling (e.g., select data in a specific time frame)
- Filtering of data
- Set alerts
- Create reports
- Compare data or benchmark results with different projects
11. What type of tasks would you like to perform with the monitoring platform?

<table>
<thead>
<tr>
<th>Task</th>
<th>Very Undesirable</th>
<th>Undesirable</th>
<th>Neutral</th>
<th>Desirable</th>
<th>Very Desirable</th>
</tr>
</thead>
<tbody>
<tr>
<td>What was the reading value of the sensor?</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>What is the trend for the sensor’s values?</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>What was the maximum/minimum value reported by a specific sensor?</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Which sensor’s values include an anomaly (deviation from a threshold)?</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Which sensor reported the higher/lower value at time T, between sensors S1 and S2?</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Identify two sensors with similar value trends in the past month.</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>What sensors are located on the same elevation?</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Was the specific sensor affected by weather patterns at a specific date?</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Are there any correlation between sensor’s value and sensor’s location?</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
</tbody>
</table>

12. Please rank, from the most to the least preferred, the format in which you would like the monitoring data to be presented:

(To do this, drag and drop the factors and rank them)

- Text (reports, articles)
- Visual (graphics)
- Audible (alarms, sounds, verbal notification)
- Text + visual
- Text + audible
- Visual + audible
- A combination of all above
13. Please indicate the degree of usefulness of the following data visualization formats:

<table>
<thead>
<tr>
<th>Table</th>
<th>Displacement After Chamber Removed</th>
<th>Total Displacement June 2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.000 mm</td>
<td>-1.567 mm</td>
</tr>
<tr>
<td>2</td>
<td>1.677 mm</td>
<td>-1.077 mm</td>
</tr>
<tr>
<td>3</td>
<td>NA</td>
<td>-1.621 mm</td>
</tr>
<tr>
<td>4</td>
<td>-2.577 mm</td>
<td>-3.182 mm</td>
</tr>
<tr>
<td>5</td>
<td>-2.602 mm</td>
<td>-2.604 mm</td>
</tr>
</tbody>
</table>

Graphs (scatter plots)

Graphs (bar charts)

Sensor location colour coded values in a 2D map

Augmented Reality - Real time sensor overlays on camera

Virtual Reality - Ability to walk through the building to see other sensors

Projected data onto the surface of monitored physical objects
14. How would you like to access monitoring data? (select all that apply)

- Online access from a website
- Online access from a registered account
- On-site access from the sensor location through a mobile device
- On-site access from a central dashboard

15. What is your preferred monitoring duration (select all that apply)

- During Construction
- Warranty Period
- 5 Years
- 10 Years
- Entire service of the Building
APPENDIX B – “SURVEY II” INSTRUMENT

Hello, thank you for helping us with our study,

Below are some things about this survey that you should know:

Study Title: Communication of structural health monitoring data of mass timber buildings in order to support decision making of relevant users

Principal Investigator: Mariapia Raggio, Ph.D.

Study team: Morvand Dilmaghani, Christopher A. Sanchez, Ph.D.

We are inviting you to take part in a research study.

Purpose: This study is designed to explore how individuals use structural health monitoring (SHM) data, and how this data can impact decision making. You must be 18 years or older to participate.

Voluntary: Participation in this study is voluntary, however in order to be included in the study results, all questions must be answered. You are free to withdraw from the study at any time, and will not be penalized for such withdrawal. For those affiliated with Oregon State University, your decision not to participate will not directly impact your relationship with your professors, or standing in the University.

Activities: The study activities include completing a brief digital questionnaire that will ask you to view and use SHM data, and provide some brief demographic data.

Benefit: This study is not designed to benefit you directly. However, information from this study could inform future efforts on how to structure and use SHM data.

Confidentiality: Other people may learn that you participated in this study but the information you provide will be kept confidential to the extent permitted by law. Data collected will not be used or distributed for future research studies.

Study contacts: We would like you to ask us questions if there is anything about the study that you do not understand.

You can call us at (541) 737-2138 or email us at mariapia.raggio@oregonstate.edu

You can also contact the Human Research Protection Program with any concerns that you have about your rights or welfare as a study participant. This office can be reached at (541) 737-8008 or by email at IRB@oregonstate.edu

If you agree to continue, please respond “yes” to a beginning question of the survey and go to the next page to start the survey.

If you do not wish to continue, please respond “no” to that question and close the window.

☐ Yes
☐ No

1. What is your age (in years)?
2. What is your gender?
- Female
- Male
- Other

3. What is your current profession (if you are a student, what is your prospective profession)?
- Architect
- Engineer
- Manufacturer
- Developer
- Other

4. What is the highest degree or level of school you have completed? If currently enrolled, highest degree received.
- High school graduate or some college
- Bachelor's degree
- Master's degree
- Doctorate degree

5. How many years of work experience do you have? (Please also provide your company affiliation)
- Less than 5 years (specify the company affiliation)
- 5-15 years (specify the company affiliation)
- 16-25 years (specify the company affiliation)
- More than 25 years (specify the company affiliation)
- No work experience

Thank you for your response.

Press the NEXT>> button to view the first scenario.
A mass timber building in Pacific Northwest has been monitored. Sensors have been installed to measure moisture content in four different locations of Cross Laminated Timber panels. Raw data of multiple moisture content readings are presented in a graph (e.g., picture below).

6. In which location did the moisture accumulate the most?

- Upper corner 1
- Upper corner 3
- Upper tendon 4
- Upper floor 6
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7. Based on this data, if you were responsible for maintenance on this building, what action would you take?

- I would check to see if there is any leakage
- I would check to see if there is any mold or stain on the floor panel
- I would inspect the floor panels to see if they are rotten
- The readings of the sensor do not look correct and probably the sensor needs to be replaced
- Nothing
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8. Which part of the graph did you use to make that decision? (please click just one region on the graph)
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9. Why did you decide to do nothing?

☐ The graph is not clear enough
☐ I need more information on how the data have been collected
☐ I need to compare this data with other published results to understand if there is a situation of concern

Good job!

Press the NEXT>> button to view the next scenario.
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A multi-story mass timber building has been monitored. Sensors (string pots) have been installed to measure vertical displacements in floors (picture below).

10. Can you select from the following graph which column experienced the greatest vertical movement and in which period? (Please click just one region on the graph)
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11. Based on this data, if you were responsible for maintenance on this building, what action would you take?

- Shore up the floor in the location of the greatest vertical movement to avoid problems of excessive deflections
- Shore up the column experiencing the greatest vertical movement to avoid problems of instability
- Check for damage in the column experiencing the greatest vertical movement
- Check for damage in the partition walls close to the location of the greatest vertical movement
- The readings of the sensor do not look correct and probably the sensor needs to be replaced
- Nothing
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12. Which port of the graph did you use to make that decision? (Please click just one region on the graph)
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13. Why did you decide to do nothing?

- The graph is not clear enough
- I need more information on how the data have been collected
- I need to compare this data with other published results to understand if there is a situation of concern
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A mass timber building in Pacific Northwest has been monitored. Sensors have been installed to measure moisture content in four different locations of Cross Laminated Timber panels. Raw data of moisture content readings are presented in a graph (e.g., picture below).

6. In which location did the moisture accumulate the most?

- Upper corner 1
- Upper corner 3
- Upper tendon 4
- Upper floor 6
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7. Based on this data, if you were responsible for maintenance on this building, what action would you take?

- I would check to see if there is any leakage
- I would check to see if there is any mold or stain on the floor panel
- I would inspect the floor panels to see if they are rotten
- The readings of the sensor do not look correct and probably the sensor needs to be replaced
- Nothing
These page timer metrics will not be displayed to the recipient.

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8. Which part of the graph did you use to make that decision? (please click just one region on the graph)
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3. Why did you decide to do nothing?

- The graph is not clear enough
- I need more information on how the data have been collected
- I need to compare this data with other published results to understand if there is a situation of concern

Good job!

Press the NEXT>>> button to view the next scenario.
A multi-story mass timber building has been monitored. Sensors (string pots) have been installed to measure vertical displacements in floors (picture below).

The table below shows vertical movement estimated for timber columns due to the combined effect of applied loads and shrinkage in a multi-story mass timber building (18 stories).

10. Can you select from the following graph, which column experienced the greatest vertical movement and in which period? (Please click just one region on the graph.)
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11. Based on this data, if you were responsible for maintenance on this building, what action would you take?

- Shore up the floor in the location of the greatest vertical movement to avoid problems of excessive deflections
- Shore up the column experiencing the greatest vertical movement to avoid problems of instability
- Check for damage in the column experiencing the greatest vertical movement
- Check for damage in the partition walls close to the location of the greatest vertical movement
- The readings of the sensor do not look correct and probably the sensor needs to be replaced
- Nothing
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![Column Shrinkage Estimation Calculated](image)

12. Which part of the graph did you use to make that decision? (Please click just one region on the graph.)

![Vertical Displacement](image)
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Column Shrinkage Estimation Calculated

Vertical Displacement

13. Why did you decide to do nothing?

☐ The graph is not clear enough
☐ I need more information on how the data have been collected
☐ I need to compare this data with other published results to understand if there is a situation of concern