Occupational noise exposures in aquaculture: assessment and mitigation strategy

by

© **Jonathan Stone**

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Abstract

Noise-induced hearing loss has become an increasing concern for employees in the aquaculture industry. Deafness, hearing loss and hearing impairment have all been identified as some of the most common injury claims from aquaculture labourers. Despite this information, noise levels and associated noise exposures in facilities have been highly undocumented. This research aims to document information on noise exposure in aquaculture and identify short- and long-term solutions to high exposures experienced by employees. Data was collected at four aquaculture facilities in Canada. Noise sources were identified and analyzed in narrowband frequency. Noise exposures were also measured and compared with the recommendations outlined by the Canadian Standards Association. Exposures were observed to be highest during tasks within the vicinity of machinery and other mechanical equipment. Short-term solutions were identified through the selection of appropriate hearing protection. Engineering design solutions were then applied to assess the feasibility of long-term solutions to reduce exposures in facilities. Numerical acoustic simulations were performed on a facility model where the Design of Experiments methodology was applied to validate its acoustical properties. The simulations showed that design solutions could be applied to reduce noise transmission and lower exposure levels throughout the facility.

General Summary

Noise is a serious issue in aquaculture. If the noise is loud enough, it can lead to hearing loss or deafness. While we know the dangers of loud noise, we know very little about the noise levels at the sites. I aimed to measure noise levels throughout each site and note any noise sources I found. I also hoped to measure noise levels seen by each employee and see if they were too high. Finally, I aimed to test different ways I could lower noise levels and stop noise from spreading. I found that noise levels were safe in most areas except for at the salmon farm. These employees worked in much louder environments because of the machinery used on the boats. I tested three ways to lower noise levels and found that all three worked well. Using these solutions could lead to a safer workspace for their employees.

Acknowledgements

I would like to sincerely thank my supervisor, Dr. Lorenzo Moro. I would also like to thank Dr. Barbara Neis and SafetyNet for their support throughout this research. Finally, I would like to thank Dr. Giorgio Burella for his assistance in developing a noise exposure measurement procedure and for his instruction on how to take accurate measurements and analyze the data.

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α	Material absorption coefficient
L_{Aeq}	A-weighted equivalent noise exposure level
$L_{Aeq,8hr}$	A-weighted, 8-hour time-weighted average equivalent noise exposure level
L_W	Noise source sound power level
T_{20}	Estimate of the reverberation time using a 20 dB decay
T_{30}	Estimate of the reverberation time using a 30 dB decay
T_{60}	Reverberation time

List of abbreviations

ACGIH	American Conference of Governmental Industrial Hygienists
CSA	Canadian Standards Association
DOE	Design of Experiments
FAO	Food and Agriculture Organization of the United Nations
HDPE	High-Density Polyethylene
HPD	Hearing Protection Device
ICEHR	Interdisciplinary Committee on Ethics in Human Research
ISO	International Organization for Standardization
NIHL	Noise-induced Hearing Loss
NIOSH	National Institute of Occupational Safety and Health
OFI	Ocean Frontier Institute
OHS	Occupational Health and Safety
SPL	Sound Pressure Level
SPL(A)	A-weighted Sound Pressure Level
STC	Sound Transmission Class
TLV	Threshold limit value

Chapter 1

Introduction and Overview

1.1 Background

The aquaculture industry has grown considerably in the last 30 years [31]. As of 2018, global aquaculture production has risen by over 500%, with nearly half of all food fish production now stemming from the cultivation of aquatic species [14]. Similar trends have been observed within Atlantic Canada, where the aquaculture industry's production output increased four-fold over 15 years from the 1990s to the early 2000s [6]. The Food and Agriculture Organization of the United Nations (FAO) estimates that over 20 million people are currently employed by the aquaculture industry, with the majority located in various Asian countries [14]. While North America is still in the early stages of industry development, over 14000 Canadians are currently employed full-time by aquaculture [15][2], with additional individuals working part-time or seasonally.

Despite the increasing importance and public awareness of aquaculture, it remains one of the most hazardous industries. Researchers in Norway have determined that fish farmers are among the most risk exposed occupational groups in the country and are second only to fishers [1][26]. Most operations at aquaculture facilities are performed year-round in outdoor areas, exposing workers to harsh weather conditions. An understanding of occupational health and safety (OHS) information is limited due to poor data collection and insufficient policies for reporting injuries [42]. For those that did report occupational injuries from the industry, the presented injury rates were high. From 2001 to 2012, there were 761 reports of occupational injuries in Norway [19]. During this time, there were less than 5500 individuals employed in the industry [13]. Brazil reported 112 cases of aquaculture-related accidents in 2012 [11] and 251 cases in 2015 [25]. It is believed that these statistics may underestimate the true injury rates globally, due largely in part to the systematic issues described above [42].

A study performed by Moreau and Neis outlined the importance of understanding OHS hazards found throughout all sectors of aquaculture [31]. They highlighted numerous hazards and categorized them into one of four categories: physical, chemical, biological, and psychological hazards. Mert and Ercan also studied industry-related OHS hazards, concentrating mainly on hazards in aquaculture plants [28]. Physical hazards such as slips, trips and falls, the use of unshielded machinery, unsafe structures, working in confined spaces and long working hours were all common. While many of the aquaculture OHS studies identify noise as another potentially dangerous physical hazard, little is known about the severity and prominence of excessive noise levels.

Moreau and Neis did discuss the dangers of excessive noise exposure and described the seriousness of noise-induced hearing loss (NIHL) in their review [31]. They did mention, however, that noise is understudied in current literature and were unable to provide information related to noise levels or measured noise exposures at facilities. Tasks associated with feed blowers, motored vehicles, and alongside machinery could all be causes of excessive noise exposure [31]. Research performed by Mert and Ercan [28], as well as Cavalli et al. [7] also describe noise as a common physical hazard, but neither provide data on average noise levels or noise exposures. There have only been three studies performed to date that provide information on noise levels in specific areas aquaculture, with only one of the studies assessing some form of noise reduction technique.

Messing and Reveret performed the first study at a fish processing plant in Quebec in 1983 [29]. Measurements were taken throughout the facility and compared to the permitted level for an 8-hour workday. The study found that noise levels often exceeded the permitted level and could reach levels as high as 88 dB(A) for employees working as checkers, and 92 dB(A) for those in shrimp sorter roles [29]. Twelve instances were documented where noise levels exceeded the permitted level, yet only 44% of employees reported noise levels at the fish plant as “much too loud” [29]. Therefore, there was still a lack of awareness of the severity of excessive noise exposures within aquaculture.

The second study measured noise levels at a salmon hatchery in South Dakota. Noise levels were measured in two fish rearing rooms, the tank room and the salmon building. Ambient noise levels of 50 and 43 dB were found in each room, respectively [3]. They then measured levels during various operating conditions at the facility. With water flowing to tanks in both rooms, noise levels increased to 73 dB in the tank room and 77.5 dB in the salmon room [3]. They also assessed two noise reduction techniques at the facility. Tank and standpipe covers were added separately and as a combination to determine their viability in reducing noise levels at the hatchery. The addition of either the tank or the standpipe covers alone was found to be ineffective in the tank room. However, using both resulted in a noise level decrease of approximately 4 dB [3]. In the salmon building, the standpipe covers were able to reduce noise levels by 2 dB when used alone and 4 dB when combined with the tank covers [3].

The third and final study was performed at a second salmon hatchery located in South Dakota. Measurements were taken during different operating conditions in the tank room and rearing pavilion at the facility. Ambient noise levels were measured as 36 dB in the tank room, with levels reaching as high as 77 dB during tank cleaning [41]. Ambient noise levels of 70 dB were measured in the rearing pavilion due to the requirement of year-round running water to the tanks. Noise levels increased during each operating condition, with levels reaching 83 dB during power washing of the tanks [41]. The permitted level was not exceeded during any of the operating conditions; however, they did indicate that hearing protection should be worn during certain tasks [41].

No other studies have documented noise exposures of workers in aquaculture or assessed design solutions to mitigate excessive noise levels. Additionally, the current literature is limited to salmon hatcheries and fish processing plants. Other sectors of aquaculture, such as research facilities and salmon farms, represent a large portion of aquaculture enterprises, but noise within these sectors has not been studied. There is also no information on individual noise exposures at an aquaculture facility, so it is difficult to assess an employee's risk of NIHL.

Noise mitigation techniques are also highly understudied in aquaculture. Without them, employees may be at significant risk of excessive noise exposure with little they can do to prevent it. Engineering design solutions are often applied in other industries and effectively mitigate excessive noise and improve the safety aspects of a facility. Using the engineering design process allows many possible solutions to be tested efficiently with accurate results, saving time and money. Through the application of design solutions, excessive noise can be eliminated or controlled at the source, reducing all employees' exposure levels.

1.2 Objectives

This thesis aims to (*i*) document noise exposures and hazardous noise sources at aquaculture facilities, as well as identify short-term solutions to high exposures experienced by workers, and (*ii*) demonstrate the propagation of noise throughout a research facility and show that engineering design solutions can be applied to mitigate any perceived noise hazards.

1.3 Organization of Thesis

This thesis is prepared in a paper-based format and is subdivided into four chapters. The outcomes of this Master of Engineering work have led to two papers under review by two separate peer-reviewed journals at the time this thesis was submitted. Ethics approval was received from the Interdisciplinary Committee on Ethics in Human Research (ICEHR) at Memorial University of Newfoundland. The ethics approval can be found in Appendix A.

Chapter 1 details an extensive background on the risk and seriousness of noise in aquaculture. Chapter 2 presents the severity of noise across four different aquaculture facilities and compares the daily equivalent noise exposure levels of employees to the prescribed threshold limit value. Chapter 3 describes a procedure for performing acoustic numerical simulations and models the noise propagation in a salmonid-based research facility. Engineering design solutions are then applied to the model and tested numerically to assess their effectiveness in reducing noise propagation and noise exposure levels for employees. Finally, Chapter 4 provides a summary and recommendations for future research.

1.4 Co-authorship Statement

I am the primary author for the two articles listed above in 1.3. As the primary author, I completed the literature review, developed the experimental procedure, performed all data acquisition and analysis, and prepared the manuscript. The contributions from the co-author, Dr. Lorenzo Moro, included reviewing the results and reviewing and revising the manuscript.

Chapter 2

Occupational Noise Exposures in Canada's Salmonid Aquaculture

2.1 Abstract

Objectives: The purpose of this study is to document noise exposures and hazardous noise sources at aquaculture facilities, as well as identify short-term solutions to high exposures experienced by workers.

Methods: Data was collected at four facilities from different sectors of the aquaculture industry; all focused on salmonids. Noise sources were identified at each facility and analyzed in narrowband frequency. Noise exposures at each facility were also measured and compared with the regulatory limits of an 8-hour time-weighted averaged, A-weighted, 85 decibel exposure level. Noise levels were assessed based on tasks performed as well as an average day of individual employees.

Results: Workers at the salmon farm were at a much higher risk of excessive noise

exposure than employees at the other three facilities due to the tasks performed and the equipment used. Salmon farm employees were frequently exposed to noise levels near or exceeding 85 dB and had extended shift lengths which further contributed to their total exposure. Feeding the salmon from the longliner and transiting on the skiff were considered the most hazardous tasks with associated noise levels above 90.0 dB(A). Across all facilities, exposures were highest within the vicinity of machinery rooms.

Conclusions: Noise exposures in the hatchery, research facility, and laboratory did not exceed the regulatory limits. Some high-risk tasks were identified, however, where employees should consider using hearing protection. Salmon farm employees were at a much greater risk of noise-induced hearing loss and should wear hearing protection when performing any major tasks on site.

2.2 Introduction

Canada has a coastline spanning over 243000 km [39], enticing many residents to participate in the commercial fisheries. In 2015, fish and seafood were Canada's second-largest single food export [16], with approximately 20% of total seafood production coming from aquaculture [15]. Over 14000 individuals in Canada are currently employed full-time by aquaculture [15][2], with additional individuals working part-time or seasonally. Working conditions are often quite dangerous at aquaculture facilities. Aquaculture operations are generally performed year-round in harsh environments and tight spaces. Occupational Health and Safety information in aquaculture is limited; however, due to "poor data collection and inefficient systematic reporting of injuries" [42]. Food quality and environmental sustainability and impact have often been prioritized over worker health and safety [7]. Regulations, legislation, and guidelines from governing bodies on OHS in aquaculture are difficult to find. They are nearly non-existent in some developing countries [42][25], due in part to the industry's rapid expansion within the past few years [11] and a lack of designation of one governing regulatory body to oversee the industry [42]. This has resulted in a limited availability of workplace injury data for aquaculture on a global level.

The Norwegian Labour and Welfare Administration received 761 reports of occupational injuries from the aquaculture industry between 2001 to 2012 [19]. During this period, less than 5500 employees were employed within aquaculture in Norway [13]. Brazil reported 251 cases of occupational injuries in 2015 alone [25]. The National Institute of Occupational Safety and Health (NIOSH) estimated an occupational injury and illness rate of 5237 per 100000 workers from 2011 to 2017 [32]. Within Canada, injuries were reported to the provincial regulatory bodies overseeing OHS in each province. While many provinces do not provide statistics on injury rates of employees in aquaculture, the province of Newfoundland and Labrador showed a lost-time incidence rate of 5.5 per 100 employees from 2010 to 2016, well above the provincial average of 1.6 [33].

The aquaculture industry is, therefore, a very high-risk occupation. However, an understanding of the OHS risks and hazards is limited globally, as very little research is available on workers and their working conditions in this field. Research in Norway found that fish farmers were the second most risk exposed occupation in the country; only fishers were at a higher risk of injury [1][26]. A study by Moreau and Neis outlined the importance of understanding OHS hazards related to different areas within aquaculture and highlighted numerous hazards categorized into physical, chemical, biological, and psychological hazards [31]. Most research on OHS in aquaculture focuses on either physical hazards such as slips trips and falls or chemical hazards related to fish vaccines and fish care. The studies often neglected the prevalence and severity of noise hazards, mainly due to the lack of information available or a lack of understanding of noise levels and employee exposures [31].

Moreau and Neis identified noise-induced hearing loss as a potential injury for employees in aquaculture related to the possibility of excessive noise exposure [31]. However, they did note that noise exposure was an understudied and not well known physical hazard within the industry, so it is unclear if excessive noise exposure is a severe risk to employees. Within their report, they identified tasks working with feed blowers, motored vehicles and alongside machinery as all being potential sources of exposures to excessive noise. Cavalli et al. also recognized noise as a potential hazard for employees, listing noise as a common physical hazard for workers in aquaculture [7], but provided no other context into the severity of this hazard or the potential causes of excessive noise at facilities. Only three other studies have documented noise levels in aquaculture.

The first studied noise levels in fish processing plants in Quebec [29]. The remaining two studied noise within different rooms in salmon hatcheries [3][41]. Messing and Reveret [29] measured noise levels in several areas throughout the processing plant in Quebec. They found noise often exceeded the permitted level for an 8-hour day at 12 different locations scattered across the facility [29]. Employees were assigned specific roles at the fish plant and often remained in the same area of the facility throughout the day to perform their required tasks. This allowed the researchers to correlate measured sound levels to roles at the facility. Specific employee roles such as checker and shrimp sorter were at a higher risk for NIHL as noise exposures in these positions exceeded the permitted levels. Only 44% of employees reported noise levels at the fish plant as "much too loud" [29], indicating there is still a lack of awareness of the severity of excessive noise exposures within aquaculture.

The second study performed by Barnes et al. monitored noise levels in a salmon hatchery located in South Dakota. They measured sound levels in two rooms, the tank room and the salmon building, where standard fish care operations were performed [3]. Ambient noise levels were measured to be 50 dB(A) in the tank room and 43 dB(A) in the salmon building. With water flowing to tanks in both rooms, noise levels increased to 73 dB(A) and 77.5 dB(A), respectively. Tank and standpipe covers were assessed as potential noise reduction techniques and were found to reduce noise levels significantly. Barnes et al. did note that all measured noise levels throughout the facility were well below the permitted levels and did not pose any significant risk for employees. However, hearing protection should be worn during certain activities to reduce the risk of prolonged exposure to noise [3].

The third study also focused on noise levels in a different salmon hatchery in South Dakota. Voorhees and Barnes measured noise levels during various operational states in the tank room and rearing pavilion at the Cleghorn Springs State Fish Hatchery. They recorded ambient noise levels of 36 dB(A) in the tank room and 70 dB(A) in the rearing pavilion. Cleaning the tanks in the tank room resulted in the highest noise levels, with noise levels as high as 77 dB(A) captured near the tanks [41]. Noise levels in the rearing pavilion were highest in the proximity of the power washer, reaching upwards of 83 dB(A). Noise levels were also high while power washing the tanks and above the tank sumps near the standpipes. Similar to the previous study of noise in a salmon hatchery, noise levels did not exceed the permitted level at any time during operation. Voorhees and Barnes did not assess any additional noise reduction techniques at this facility but did state that the application of these techniques is advisable [41].

To our knowledge, there have been no other studies documenting noise levels in aquaculture facilities. Areas of aquaculture, such as research facilities and farms, have been completely ignored in previous studies. Additionally, individual noise exposures of employees have never been studied to document the individual risk of exposure to excessive noise and NIHL. This research aims to increase the knowledge of noise levels observed and noise exposures of workers in salmonid based facilities in aquaculture.

2.3 Methodology

Figure 2.1 reports the flowchart of activities performed in the research presented in this paper.

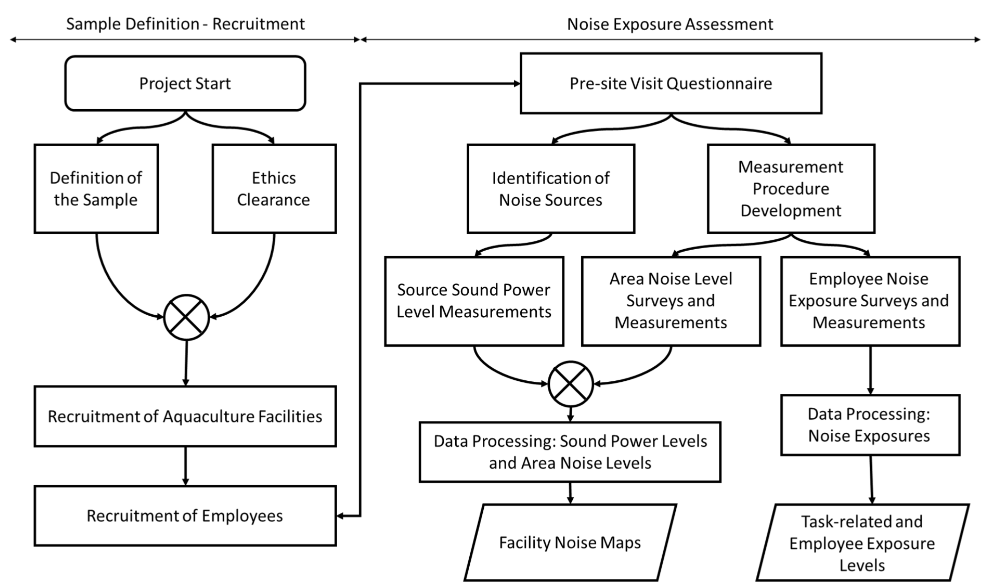


Figure 2.1: Flowchart for the research outlined in this paper.

2.3.1 Recruitment

Ethics clearance was received from the ICEHR at the Memorial University of Newfoundland before the start of participant recruitment. The file number of the approved ethics application is 20192681-EN. All participation was to be voluntary with written, informed consent from participants. All personal identifiers and individual results were to be kept confidential; only the primary researcher responsible for analyzing the data and sharing the results had access to this information. Phone calls and site visits were made to recruit companies that owned and operated aquaculture facilities in Canada. As a result, 4 aquaculture companies with facilities of varying operations were recruited for the research and a total of 10 employees across the four facilities. Individual participants were recruited in-person at each site before the start of measurements at their workplace. Once the measurements were completed and the data processed, de-identified aggregated results were shared with each participant and with the employers or their representatives. The latter also received the results from the indoor noise mapping of their facilities.

2.3.2 Questionnaires

Before each noise survey, we administered a structured questionnaire to participating facility managers. The questionnaires aimed to collect the following information:

- The number of employees working at the facility;
- the average shift length of employees;
- the main noise sources present on site;

- the main activities performed by employees;
- the use of hearing protection at the facility;
- and the type of hearing protection device (HPD) used (if applicable).

Based on the results from the questionnaires we developed a general measurement procedure.

Before starting noise measurements, all employees were briefed on the research before providing consent to participate in the study. An effort was made to have employees from different roles participate in the study to capture a more realistic approximation of their subjected noise levels. Each employee was equipped with a Type 4448 personal noise dosimeter to wear throughout their shift. They were instructed not to talk directly into the device as this may influence the measured noise exposures. The noise dosimeter was removed during breaks where the employee left the site as these breaks were not considered part of the operations within the facility. Employees were asked to complete an activity log throughout the day, providing details of the tasks performed and the times at which they occurred. During the surveys, the research team was observing the participants and filling out an activity log for each employee to validate the information provided by the participants and document any tasks the employees may not have captured. During the assessment of personal noise exposures, we also mapped noise levels in each room of the tested facilities, and identify any hazardous noise source.

2.3.3 Noise surveys

Noise surveys were performed to i) map noise in each facility, ii) assess occupational noise exposures, and, iii) identify appropriate hearing protection. All noise surveys were performed in accordance with the standards and regulations set by the International Organization for Standardization (ISO) and the Canadian Standards Association (CSA).

Noise mapping of the surveyed facilities

Initial noise surveys were performed in each facility to understand the propagation of noise throughout each facility and identify areas with hazardous noise levels. Measurements were taken in accordance with the ISO Standard [23]. We measured noise at multiple locations in each room to map noise levels taking into account steady-state and transient noise. For each measuring point, we performed a minimum of three 5-minute measurements and we then averaged the resulting 1/3 octave band spectra. The spectra were then averaged by room to determine a single representative noise level for that space. In each room, we also identified relevant noise sources responsible for the overall noise level and calculated their noise power as described in ISO 3746:2010 "Acoustics - Determination of sound power levels and sound energy levels of noise sources using sound pressure - Survey method using an enveloping measurement surface over a reflecting plane." [22]. When the noise surveys were performed on vessels, we followed the procedure presented in [5] to assess noise levels and characterize the noise sources. A handheld microphone was used to measure sound levels in each position in accordance with the procedure outlined in CSA Z107.56-18. Measurements were taken at head level [9], and at an arm's length away to reduce any possible effects of sound reflecting from the body [30]. All noise source measurements were analyzed in the narrowband frequency range, in order to identify each relevant noise source, and in one-third octave bands to estimate noise levels.

Assessment of occupational noise exposures

Occupational noise exposures were then assessed in accordance with a selection of provincial, national, and international regulations and standards. Provincial occupational health and safety regulations were followed to determine the appropriate procedures to be applied during data acquisition and analysis. These regulations required all noise exposure measurements to be performed in accordance with CSA Z107.56 "Procedures for the Measurement of Occupational Noise Exposure" [9]. Threshold limit values (TLVs) were obtained from the American Conference of Governmental Industrial Hygienists (ACGIH). The ACGIH states that an A-weighted, eight-hour time-weighted average noise exposure, $L_{Aeq,8hr}$, should not exceed 85.0 dB(A) without the use of proper hearing protection [34]. Table 2.1 lists the noise exposure limits for durations other than eight hours. In our surveys, we applied a combination of task-based and full-day measurements to assess the noise exposures at the four aquaculture facilities. Measurements were recorded for each employee throughout their entire workday to represent an average day or shift for that person. We then assessed the A-weighted equivalent noise exposure, L_{Aeq}, associated with each work-task by using the information in the activity logs filled out by participants, as described in Section 2.3.2.

Table 2.1: ACGIH sound threshold limit values (TLVs) [34].

Duration Per Day [Hours]	Sound Level [dB(A)]
16	82
8	85
4	88
2	91
1	94
0.5	97
0.25	100

Identification of appropriate hearing protection

Recommendations for appropriate hearing protection were provided when noise exposures approached hazardous levels. Potentially hazardous noise exposures were considered to be exposure levels greater than or equal to 75.0 dB(A) as it has been shown that extended exposure to levels above 75.0 dB(A) can result in hearing impairment [36]. All recommendations of hearing protection were made in accordance with CSA Z94.2 "Hearing Protection Devices - Performances, Selection, Care and Use" [10].

2.3.4 Instrumentation

Personal noise exposure measurements were taken with a personal noise dosimeter. A Brüel & Kjær® Type 4448 noise dosimeter was equipped to the shoulder of each participant to monitor noise exposures throughout the day. Each dosimeter was calibrated using a Larson and Davies® calibrator model CAL200 before and after taking measurements. A Class 1 model 378B02 ICP handheld microphone by PCB Piezotronic® connected to a National Instruments® model 9234 BNC input card that was connected via USB to a Dell® Latitude 5480 laptop computer was used to capture sound levels in areas scattered throughout each facility. These measurements were used to map noise exposures across the facility and identify key noise sources. The microphone was calibrated each day before and after any measurements were taken using the Larson and Davies® calibrator model CAL200. Post-processing of data from the handheld microphones was performed using National Instrument's LabVIEW®.

2.4 Results

This section presents the results from the noise surveys. After a presentation of the surveyed facilities (Section 2.4.1), we present the results from the questionnaires administered to the site managers (Section 2.4.2). Section 2.4.3 shows the noise maps of the facilities and the sources that we identified as responsible for any high noise levels. The results from the assessment of occupational noise exposures of the employees are presented in Section 2.4.4 and in Section 2.4.5.

2.4.1 Surveyed Facilities

Table 2.2 presents the four facilities included in the research presented in this paper. All the facilities were specialized solely on salmonid operations. The first facility represented a hatchery consisting of a larger tank room in the middle, with several smaller rooms branching off. There were also four large tanks located outside of the facility that were included in the study. One of the employees regularly divided his day between the hatchery and an in-house processing plant. The study included measurements from the processing plant as it was considered relevant to the daily operations of the facility and its employees. The second facility operated as an aquaculture research facility. The building was a multi-level building with many separate rooms for different research activities. Some of the main areas examined for noise were the large broodstock room, the hatchery room, the office space and the filtration room. The third facility was an aquaculture laboratory studying illnesses and diseases in salmonids. The containment area was located on the first level of the building with all offices and laboratories on the second level. The fourth and final facility included in the study was a salmon farm. The farm consisted of a series of cages and nets to grow the salmon and used a longliner to perform most operations on site. Two feeding barges were also used by employees while feeding the salmon. The site manager performed the majority of his tasks using an aluminum skiff, a small open-concept vessel with an outboard motor. Noise level measurements were performed onboard each of these vessels during different operating conditions. It should be noted that while four employees work at the salmon farm, only three consented to participate in this research.

Table 2.2: Sampled aquaculture facilities.

Facility ID	Facility Type	Species	# of Emp.	Emp. Role	Emp. ID
FAC001	Hatchery	Salmonid	2	Manager Labourer	H01M H02L
FAC002	Research	Salmonid	3	Labourer Labourer Labourer	R01L R02L R03L
FAC003	Laboratory	Salmonid	2	Manager Labourer	L01M L02L
FAC004	Farm	Salmonid	4	Manager Labourer Labourer	F01M F02L F03L

2.4.2 Questionnaire Findings

The information gathered through the site visits were compared to the findings from the preliminary questionnaires completed by the site manager at each facility. The managers' responses have been captured in Table 2.3.

Table 2.3: Findings from facility manager questionnaire.

Question	Hatchery	Research Facility	Laboratory	Salmon Farm
Number of employees?	3	10	3	4
Major noise sources?	Filters Pumps Blowers	Air blower O_2 separator Air conditioner Blender Pumps	Ventilation Drum filters Freezers/fridges Compressors Autoclaves Lab equipment	Longliner engine Outboard motor Generator Deck crane
Activities performed?	Fish feeding Spawning Cleaning filtration Office work	Produce air produce O_2 Cool air Blend food Pump water	Animal care Experimentation Maintenance Lab activities Office work	Feeding salmon Net cleaning Bridle cleaning Dive support
HPD used?	No (Provided)	Yes	No	Yes
HPD type?	Over the ear	Ear plugs / Over the ear	N/A	Ear plugs

2.4.3 Facility Noise Maps

Figures 2.2, 2.3, 2.4 and 2.5 show the noise map of the surveyed facilities. A colour grid was applied to the map based on the noise level in each room. Green represents any A-weighted noise level below 75.0 dB(A). Yellow indicates noise levels measured between 75.0 dB(A) and 85.0 dB(A). Red was applied to an area of the facility where the noise levels were found to be more than 85.0 dB(A). In the Figures, an X denotes the locations of noise measurements taken with the handheld microphone.

The noise map of the hatchery is shown in Figure 2.2. The measurements found that noise levels were highest in areas where hazardous noise sources had been identified. None of the exposure levels exceeded 85 dB(A); however, they may still be dangerous for employees. Areas, where employees may be at risk of NIHL, have been highlighted in yellow on the facility map.

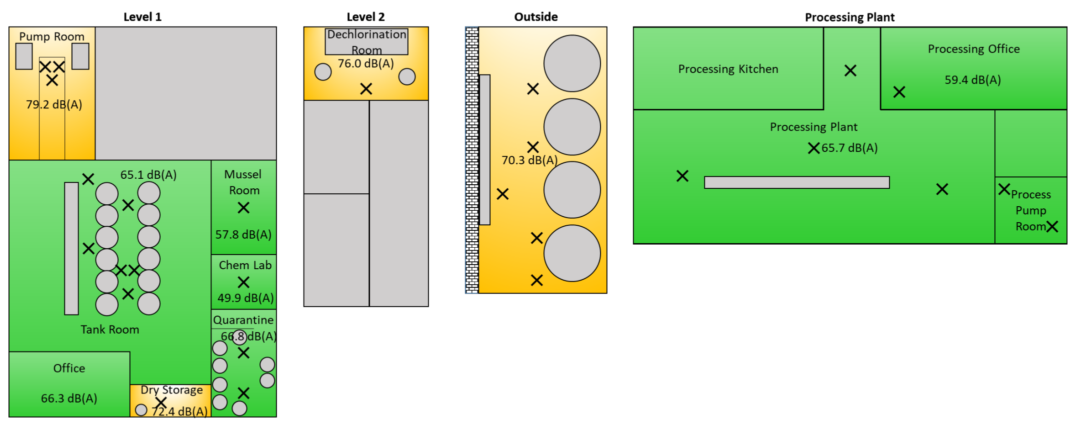


Figure 2.2: Noise map and location of measurements for the hatchery. Green represents areas with safe noise levels. Yellow represents areas with potentially hazardous noise levels.

Figure 2.3 shows the noise map developed for the research facility. Noise levels were highest in the Filtration Room, where the majority of the machinery was located. Sound from this room was found to travel to other areas of the facility, such as Prep Room B and the Broodstock Room, where potentially hazardous levels were also measured. All other areas of the facility were well below hazardous levels and did not present a risk of NIHL to employees.

Figure 2.4 displays the noise map for the laboratory. Noise levels were found to be well below any hazardous level in the majority of the facility. The only area of concern at the laboratory was in the Waste Treatment Room, where a noise level of

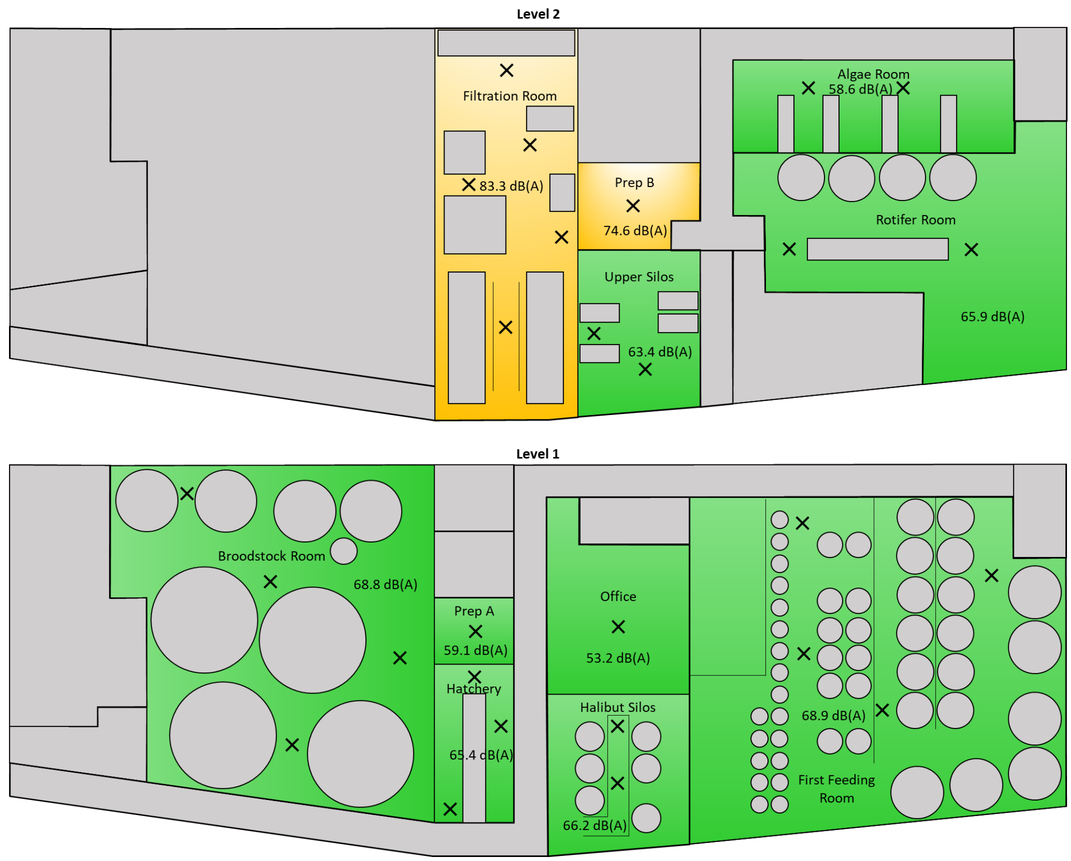


Figure 2.3: Noise map and location of measurements for the research facility. Green represents areas with safe noise levels. Yellow represents areas with potentially hazardous noise levels.

72.6 dB(A) was recorded. This noise level could increase to values higher than 80.0 dB(A) when cleaning of the filtration system was performed. This is represented in the figure by the diagonal line through the Waste Treatment room.

The noise map for the salmon farm is shown in Figure 2.5. The areas of concern included the longliner, the barge and the skiff. The aft section of the longliner and the entire barge were assigned two colour codes based on the L_{Aeq} with and without the feed blower in operation. While the feed blower was on, the noise level throughout the entire longliner increased to hazardous levels where employees were at risk of NIHL. Results were similar on the skiff, as the operator was seated near the engine.

Figure 2.4: Noise map and location of measurements for the laboratory. Green represents areas with safe noise levels. Yellow represents areas with potentially hazardous noise levels. The diagonal line in the Waste Treatment room represents normal operating conditions (lower) and cleaning operations (upper).

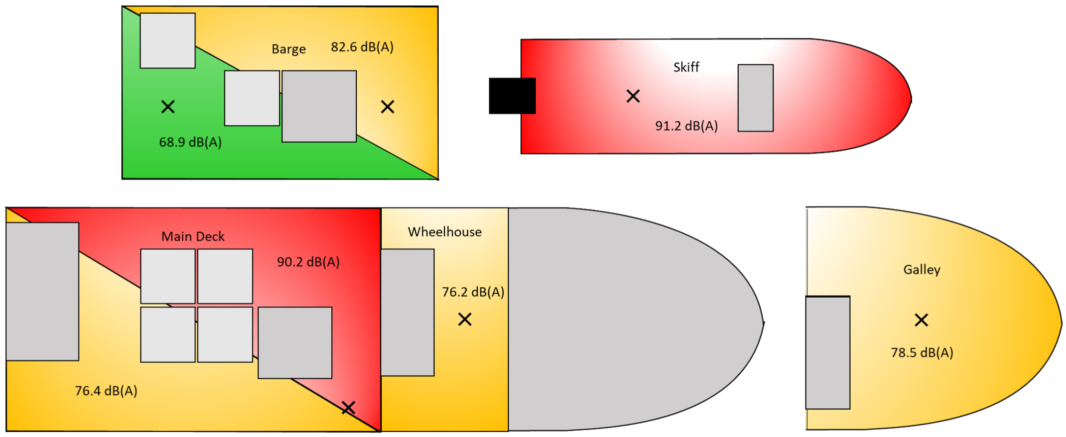


Figure 2.5: Noise map and location of measurements for the salmon farm. Green represents areas with safe noise levels. Yellow represents areas with potentially hazardous noise levels. Red represents areas with hazardous noise levels. The diagonal line represents transiting conditions (lower) and feed blower operation (upper).

The noise sources in each facility, and their corresponding Sound Power Levels, L_W, are shown in Table 2.4.

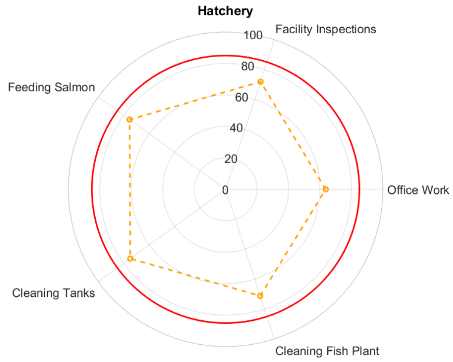
Table 2.4: Potentially hazardous noise sources identified at each facility.

Facility Type	Noise Source	L_W [dB]
Hatchery	Compressor	78.8
	Filter System	86.8
	Generator System	95.1
	Dechlorination System	85.4
Research Facility	Generator	91.6
	Compressor	102.7
	Water Pipe	90.8
Laboratory	Compressor	90.3
	Treatment Drums	88.9
	Diaphragm Pump	88.5
Salmon Farm	Longliner Engine	89.4
	Feed Blower (Longliner)	102.9
	Feed Blower (Barge)	103.5
	Outboard Motor	119.8
	Portable Generator	106.8

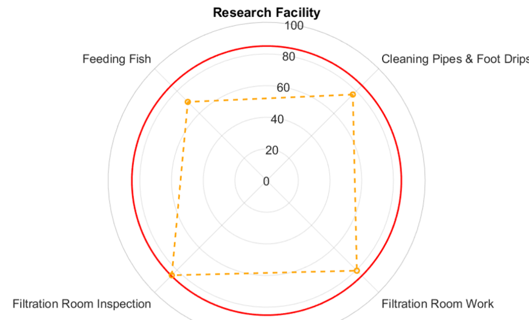
2.4.4 Task-based noise levels

The activities performed by employees at each facility were monitored to document common tasks at the site. Noise exposure measurements were captured for all major tasks using the personal noise dosimeter attached to the individual performing the task. All personal noise exposures were compared to the 8-hour exposure threshold limit value of 85 dB(A). Any measurements that exceeded the prescribed regulatory limit were considered hazardous.

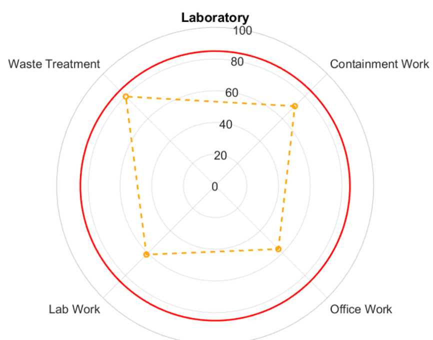
Five major tasks were identified at the hatchery. All five tasks resulted in noise exposures well below the allowable limit and did not warrant the use of hearing protection. The research facility had four common tasks shared between the three employees. Neither task exceeded the 85 dB(A) threshold, however working within the filtration room, especially while performing a filtration room inspection, results in potentially hazardous levels above 80.0 dB(A). The two employees at the laboratory often participated in the same four tasks throughout the week. Tasks performed outside of the containment area, such as the office and lab work, were well below the allowable limits. Working within the containment area, however, saw exposure levels approaching hazardous levels. Work at the salmon farm consisted of four major tasks, each of which approached or exceeded the regulatory limit. During these tasks, employees are advised to wear hearing protection to reduce their risk of NIHL. Figure 2.6 shows the noise levels associated with each task at the four facilities. The red line represents the 85 dB(A) regulatory limit in each plot.



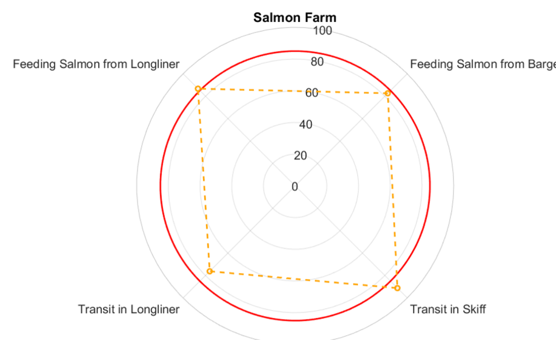
(a) Hatchery



(b) Research facility



(c) Laboratory



(d) Salmon farm

Figure 2.6: Task-related noise exposure levels (L_{Aeq}) of activities performed at the four facilities. The red line represents an 85 dB(A) noise exposure level.

2.4.5 Employee noise exposure levels

The noise measurements were also analyzed as an 8-hour equivalent personal noise exposure for each employee. The noise exposure associated with the tasks included in the employee's average day was used to develop a workday equivalent exposure level. The equivalent workday exposure was then converted into an 8-hour equivalent exposure level to be easily compared to the regulatory limits. A dosage of exposure was also calculated for each employee by relating each individual $L_{Aeq,8hr}$ to the 8-hour time-weighted average limits provided by ACGIH. An employee with an 8-hour equivalent exposure level of 85 dB(A) had a 100% dosage level. Figure 2.7 displays the individual $L_{Aeq,8hr}$ and dosage level of each employee.

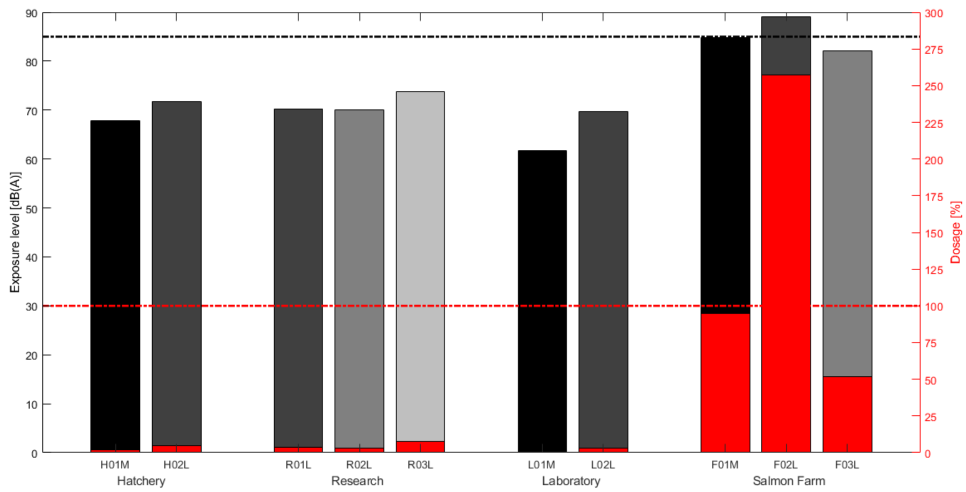


Figure 2.7: 8-hour equivalent personal noise exposure levels ($L_{Aeq,8hr}$) and noise doses of participating employees.

The employees from the hatchery, research facility, and the laboratory each had equivalent exposure levels well below the 85 dB(A) regulatory limit. They should not be at significant risk of NIHL. However, the three employees from the salmon farm are at a higher risk of NIHL as they have 8-hour equivalent exposure levels near or above 85 dB(A). Steps should be taken to either reduce the exposure time of these employees or reduce their perceived noise levels using the appropriate hearing protection.

2.5 Discussion

2.5.1 Occupational Noise Exposures

All A-weighted, 8-hour time-weighted average noise exposures for employees were compared to the ACGIH-TLV of 85 dB(A). The results from the full-day and task-based measurements (Section 2.4.4 and Section 2.4.5) both showed that the majority of the participating employees did not exceed the exposure limit. Employees at the first three facilities fell well below the ACGIH threshold in the range of 60 to 75 dB(A). R03L had the highest exposure from both methods, with an overall 8-hour noise exposure of 74.7 dB(A). The measurements at the salmon farm were much more concerning as all three employees had a $L_{Aeq,8hr}$ greater than 80.0 dB(A) with consequent higher risk of NIHL. The 8-hours noise exposure for F02L exceeded the ACGIH-TLV of 85.0 dB(A), with a daily noise dose that exceeded 250%.

The employee roles were compared between facilities to determine if there was any correlation between position and noise exposure level. Several similarities were observed between employees at the hatchery, the research facility and the laboratory. The site manager at each facility (if included in the study) had the lowest noise exposure of all employees. The site managers at the hatchery and the laboratory had identified that they spent most of their day in an office. The office space was isolated from the rest of the facility and equipment, reducing the exposures of these employees. The office spaces were tranquil, with ventilation systems being the only noise source. Labourers and researchers were often subjected to higher noise levels as the majority of their day consisted of performing tasks related to fish care and facility upkeep. These employees at the three facilities performed similar tasks throughout the day in similar environments, which resulted in comparable noise exposures between workers. The salmon farm does not follow this trend as the working conditions were significantly different from those observed at the hatchery, the research facility, and the laboratory. The site manager of the salmon farm performed many of the same tasks as the labourers at the facility. They also spent the majority of the day working alongside the other employees. For this reason, the site manager's noise exposure level was quite similar to those measured for the two labourers on site.

Specific tasks were noted to be related to high noise exposures for workers across all facilities (Section 2.4.4). At all three on-land facilities, the task of maintaining or checking the Filtration/Waste Treatment Room resulted in noise exposures of approximately 80 dB(A) and above. Cleaning the tanks and feeding the fish were two other everyday activities that resulted in exposures between 70 and 75 dB(A); however, it may still be beneficial for employees to wear hearing protection during these activities in some regions of the facilities. The task of feeding the salmon was performed differently at the salmon farm and was determined to be much more hazardous for employees, reaching levels of up to 86.7 dB(A). Transit to the site was another critical task at the salmon farm that varied depending on the vessel being used. Transiting in the longliner was on the lower end at 76.2 dB(A) while operating the skiff resulted in exposures of 91.2 dB(A). Both tasks have been identified as hazardous to employees and care should be taken to reduce the risk of NIHL.

2.5.2 Noise mapping and sources

As seen in Section Section 2.4.3, the measured noise levels at the salmon farm are significantly higher than those observed at the other three facilities. The main reason is that the hatchery, research facility, and laboratory were all located in buildings on-land, and the main noise sources were isolated from the rest of the facility. At the salmon farm, workers were required to perform all tasks near machinery due to limited space onboard the vessels, and the equipment used to feed the salmon was install on the the vessel's main deck where the personnel was working.

Common noise sources were identified to aid in understanding the causes of high noise exposures and noise levels throughout areas of each facility. The use of generators and pumps was found in all four facilities, representing potentially hazardous noise sources. This piece of equipment had a significant impact on the noise levels observed in its surrounding area. The hatchery, the research facility, and the laboratory had pumps located in rooms used for water filtration. Despite the room was generally fully enclosed to try to minimize the transmission of sound to other areas of the facility, sound was found to escape these rooms to some degree and effect noise levels in surrounding areas, which could disrupt the normal operations of the employees. A portable generator was also used in the salmon farm for cleaning the cage and assisting in other diving operations. The crew placed this generator on the deck of the barge close to all workers. The use of the generator could pose a serious hazard to employees while in use. In addition, the salmon farm had some other major noise sources that were the cause of high noise levels. The hand-guided feed blower used while feeding the salmon provided excessive noise levels upwards of 90.2 dB(A). This device was used for 6 hours a day by each labourer. Workers were required to stand directly next to the blower during use to control the distribution of feed. The engines onboard the longliner and the skiff posed another risk for employees. The labourers spent much of their day onboard the longliner, with its engine producing a steady noise level of 78.5 dB(A). The engine on the skiff was even louder at 91.2 dB(A).

2.5.3 Suggested hearing protection

Suggestions for hearing protection to be worn at the sites were made in accordance with CSA Z94.2-14. This standard recommends Class C hearing protection for exposures less than or equal to 90 dB(A) and Class B for exposures less than 95 dB(A). While the majority of exposure levels related to tasks did not exceed 90 dB(A), it is still recommended that employees use Class B hearing protection to reduce the risk of hearing loss. Class B hearing protection would also account for any instances where noise levels may be higher than those captured during data collection. In the farm, the use of hearing protection with active noise cancelling is advisable to improve communication among workers, thus improving safety on the vessels [4].

2.5.4 Noise awareness

The results from the surveys administered to the facility managers show that they were aware of noise at their facilities and were able to identify all significant noise sources on site. Three of the four facilities all said they have actively taken steps to reduce noise exposures by providing employees with some form of hearing protection. Only the laboratory said nothing had been done at the facility to reduce the exposure levels of employees. When asked if employees wear hearing protection, however, only two of the facilities stated employees wear the appropriate hearing protection during hazardous tasks. Employees at the hatchery and the laboratory did not use any form of hearing protection when exposed to hazardous noise levels, even when these were provided.

2.6 Conclusion

In this paper, we presented the results from extensive noise surveys performed in 4 facilities of the aquaculture industry, with the aim to inform key stakeholders of any risk of occupational noise exposures. We found that noise was particularly high in the salmon farm, where the feed blower and the vessels' engines were the main sources contributing to these hazardous noise levels. In the hatchery, the laboratory, and the research facility, employees' $L_{Aeq,8hr}$ were lower than the ACGIH Sound Threshold Limit Values. Nonetheless, we identified areas in these facilities with high noise levels where labourers should wear adequate hearing protections. Facility managers were aware of any hazardous noise levels and noise sources in their facilities, but employees not always were wearing hearing protections when required. From our analysis we can draw the following recommendations:

- Since generators and compressors are common sources of noise in all the facilities, these should be properly isolated via resilient mounts and enclosed in insulated spaces. All doorways accessing rooms with this equipment should always kept closed;
- Salmon farms should switch to automatic feed blowers, which would remove the necessity of having a worker nearby during feeding;
- Vessels used in salmon farms should have the engine room properly insulated, when equipped with inboard engine, or the engine case insulated, when equipped with outboard motor;
- When the engineering solutions proposed above are not implemented, employees should wear Class B hearing protection. If they are working on vessels, the

hearing protections should allow easy communication.

This study focused solely on the finfish sector but did not include any processing plants due to a lack of response from companies. The shellfish sector was excluded at this stage but should be studied due to its vast differences from the finfish sector in its operations and equipment. Future research aims to address these areas by including additional facilities focused on finfish operations and working with companies in the shellfish sector to increase company participation.

Chapter 3

Design Solutions to Mitigate Hazardous Noise Levels in Aquaculture Facilities

3.1 Abstract

Noise-induced hearing loss has become an increasing concern for employees in the aquaculture industry. While many researchers have identified noise as a severe hazard, information on noise levels at aquaculture facilities has been undocumented. This paper aims to document noise levels at an aquaculture research facility, as well as assess long-term design solutions to reduce noise transmission and improve working conditions for employees. Noise levels were measured in high traffic areas to capture the propagation of noise at the facility. This data was used in conjunction with measured reverberation times and source sound power levels to develop a numerical

model of the site. The design of experiments methodology was applied to optimize any unknown acoustic properties of each room numerically. The model provided a noise map of the facility, highlighting potentially hazardous noise levels in the facility's Filtration room that were transmitted to nearby areas. Three engineering design solutions were then applied to reduce the transmission of noise throughout the facility. Closing doors leading to the Filtration room reduced noise levels by 6 dB. Applying acoustic insulation proved to be extremely effective, reducing noise levels in select rooms up to 20 dB.

3.2 Introduction

Employment in aquaculture is one of the most hazardous occupations globally. Researchers in Norway found that fish farmers were second only to fish harvesters as the most risk exposed occupation in the country [1][26]. The Norwegian Labour and Welfare Administration received 761 reports of occupational injuries from aquaculture between 2001 and 2012 [19] with less than 5500 individuals employed across the entire industry at this time [13]. Similar statistics were observed in other countries. Brazil reported 112 cases of occupational accidents related to aquaculture in 2012 [11] and 251 cases in 2015 [25]. The National Institute of Occupational Health and Safety estimated an occupational injury and illness rate for aquaculture of 5237 per 100000 employees in the United States of America [32]. These statistics are likely significantly underestimating the true injury rates globally, due largely in part to a lack of reporting and inadequate enforcement by governing bodies. The majority of aquaculture sites are small and independently owned and operated, making monitoring and regulating these sites nearly impossible. It also adds pressure to employers enticing them not to report injuries in fear of losing their business. The lack of reporting and the difficulties with overseeing the privately owned enterprises has proved to be a challenge when trying to understand the occupational health and safety risks and hazards in aquaculture.

Research focused on the OHS risks and hazards in aquaculture is limited, and generally studies the issue on a macroscopic level. In 2009, Moreau and Neis provided a review of OHS hazards in Atlantic Canadian aquaculture. They discussed the importance of understanding hazards found throughout all sectors of aquaculture and identified several known hazards related to one of four categories [31]. Mert and Ercan also studied occupational health and safety in aquaculture, concentrating mainly on hazards in aquaculture plants [28]. Common hazards identified in the study included slips, trips and falls, the use of unshielded machinery, unsafe structures, working in confined spaces and long working hours. The majority of research describes in detail the risk associated with many physical and chemical hazards. However, it neglects some other important hazards that are known to be present in most aquaculture facilities. One such hazard is excessive noise exposure, which has received little attention from the current literature despite being a common hazard in aquaculture.

Moreau and Neis did discuss the dangers of excessive noise exposure in their review and identified noise-induced hearing loss as a potentially serious injury with long-term effects [31]. They did not, however, provide information on noise levels or measured noise exposures at facilities due to the topic being understudied and not well known. Within their report, they suggested that tasks associated with feed blowers, motored vehicles, and alongside machinery could all contribute to excessive noise exposures of workers. Noise was also mentioned briefly as a common physical hazard in studies by Mert and Ercan [28] and Cavalli et al. [7], but neither report provided any other information related to average noise levels or common sources of noise. Only three studies have provided insight on noise levels in aquaculture, only one of which studied noise reduction techniques.

The first study focused on noise levels in fish processing plants in Quebec [29]. The researchers measured noise levels throughout the facility; finding noise often exceeded the permitted level for an 8-hour day [29]. Roles such as checker and shrimp sorter were noted as hazardous positions in the plants, with noise levels reaching as high as 88 dB(A) for the checkers and 92 dB(A) for the shrimp sorters. In total, they documented 12 instances where noise at the facility was excessive; however, solutions to this problem were never addressed.

The second study monitored noise levels in a salmon hatchery located in South Dakota. All measurements were taken at the Cleghorn Springs State Fish Hatchery in two different rooms. Voorhees and Barnes focused on noise levels during a series of operational states in the tank room and rearing pavilion at the facility. Ambient noise levels in the tank room were measured to be 36 dB, which increased to as high as 77 dB during tank cleaning [41]. They measured the ambient noise level to be 70 dB in the rearing pavilion due to the running water that was required year-round for hatchery production. Sound levels in the rearing pavilion increased as different operations were performed, with the highest noise levels of up to 83 dB were observed during power washing the tanks. None of the noise measurements at the facility exceeded the permitted level at any time during operation; however, they did indicate that caution should be taken and hearing protection worn during particular tasks [41].

The third study also focused on noise levels in a salmon hatchery at another location in South Dakota. Barnes et al. measured sound levels in the tank room and the salmon building at the McNenny State Fish Hatchery. They measured the ambient noise level in the tank room to be 50 dB, while the ambient noise level in the salmon building was only 4 dB [3]. One of the operational conditions tested had water flowing to tanks in both rooms. They observed an increase in noise level to 73 dB in the tank room and 77.5 dB in the salmon building. Barnes et al. did note that the addition of flowing water did not result in noise above the permitted levels. Still, they suggested the use of hearing protection during certain activities. They also assessed a noise reduction technique during the study to determine if noise levels could be reduced at the facility. The proposed solution was the implementation of covers over the salmon tanks and the nearby standpipes. In the tank room, the addition of either the tank covers or the standpipe covers had little effect on the overall noise level measured. However, with both covers in place, noise levels were reduced by approximately 4 dB [3]. In the salmon building, the standpipe covers were able to significantly reduce noise levels in the room, reducing levels by 2 dB when used alone and 4 dB when paired with the tank covers.

To our knowledge, no other studies have been performed documenting noise levels and reduction techniques in aquaculture facilities. While some studies have suggested that noise is a serious hazard that requires more attention, there is no data available on noise levels in specific sectors of aquaculture. Engineering design solutions are frequently used in other industries to improve the health and safety aspects of the workplace. However, this approach has not yet been incorporated into the aquaculture industry, when it comes to mitigating occupational noise exposures. This papers aims to document noise levels at an aquaculture research facility and shows that engineering design solutions can be applied to mitigate any perceived noise hazards.

3.3 Methodology

Figure 3.1 presents the flowchart of activities performed in the research presented in this paper.

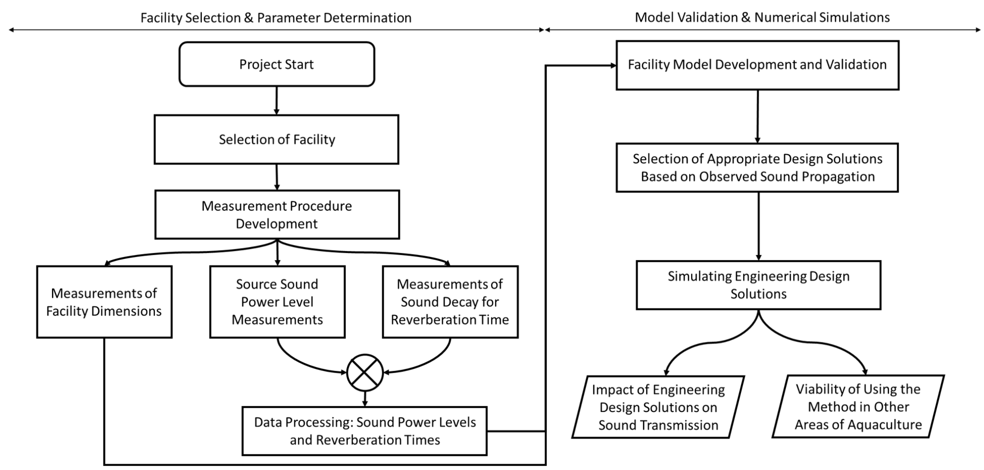


Figure 3.1: Flowchart for the research presented in this paper.

3.3.1 Facility Selection

The research facility included in the noise exposure assessments (Chapter 2) was selected to test the viability of engineering design solutions in mitigating excessive noise levels and noise propagation. This facility was selected as it represented an average aquaculture site with regular tasks that were common among three of the indoor facilities. The research facility performed many tasks similar to that of a hatchery where they reared salmon populations, as well as other salmonids, from birth. They also provided salmon to local farms and other research facilities once the fish had grown to size. Additionally, they performed some experiments on site related to the growth and health of their fish.

The facility consisted of a series of rooms used to rear the salmon. The Broodstock room contained a number of large tanks used to house the larger salmonids. The Hatchery was used to birth the salmonids, while the First Feeding room contained the small to medium sized fish population. An Office was also located on the first floor for the employees. The second floor had a Filtration room used to clean the water and create pure oxygen to be supplied to the tanks. The remaining rooms on the floor were primarily used for research activities. Figure 3.2 shows the layout of the facility.

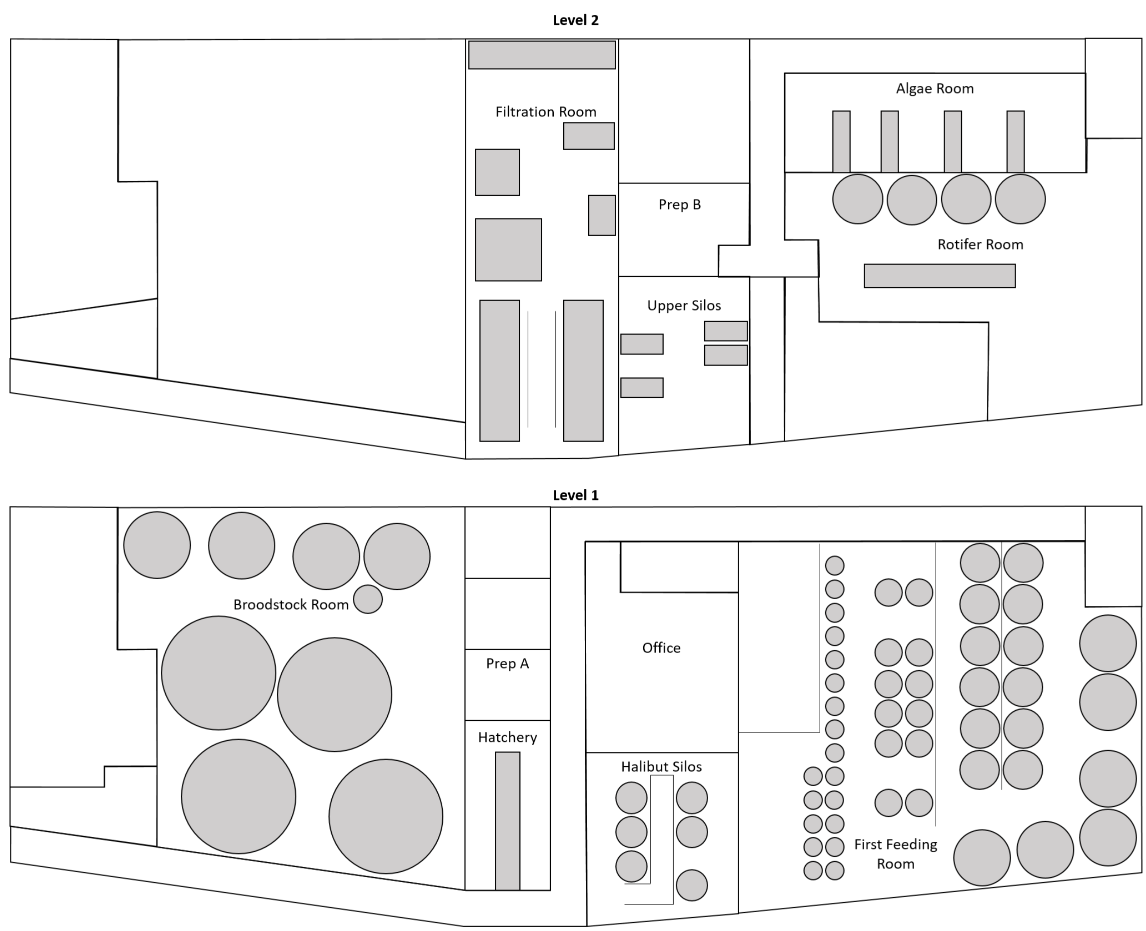


Figure 3.2: Layout of the research facility. The grey circles represent the fibreglass tanks. Other machinery and equipment were also denoted by grey rectangles.

3.3.2 Measurement Procedure

Measurements were taken in areas of the research facility where employees identified most of their tasks to occur. They highlighted the Broodstock room, the Hatchery, the Office, the First Feeding room, the Rotifer room, the Filtration room, and Prep room B as high traffic areas.

Reverberation time was measured in each of the rooms listed above using a sound generator and the handheld microphone. The reverberation times of areas within the facility were measured following the procedures outlined in ISO 3382-2:2008 "Acoustics - Measurement of room acoustic parameters - Part 2: Reverberation time in ordinary rooms" [21]. The measurements were performed in line with the engineering method where appropriate to provide an appropriate level of accuracy. It also allowed the measured reverberation time to be used to accurately predict the absorption coefficients of materials in a complex room. A noise level was selected for the source to provide a sufficient increase in SPL above the background noise of the room to allow for an accurate decay of sound, as required by [21]. A linear 60 dB decrease was not easily achieved across all octave bands; therefore, the T_{30} was used to estimate the reverberation times instead.

The measurements of source sound power level were performed in accordance with ISO 3746:2010. The standard states that the measurement surface of a source can be modelled in one of four ways. Either a parallelepiped, a hemisphere, a half-hemisphere, or a quarter-hemisphere (each of constant radius) is suggested [22]. For simplicity and continuity, each source analyzed at this facility used a variation of the spherical method with a radius of one meter. This means the microphone was placed one meter away from the source at each of the measurement positions and averaged to determine the associated sound power level.

A-weighted SPLs (SPL(A)) were taken throughout the facility to validate the sound power levels of each source. For each measuring point, we performed a minimum of three 5-minute measurements and we then averaged the resulting 1/3 octave band spectra. The spectra were then averaged by room to determine a single representative noise level for that space.

3.3.3 Numerical Simulations

The dimensions of the entire facility were obtained using a combination of the handheld laser measurer and a facility map provided by the site manager. The dimensions were used to make a replicate model of the research facility in SketchUp®. The completed model was exported into ODEON Room Acoustics Software® for the numerical simulations. This software package uses ray tracing to represent the propagation of sound through a medium. Ray tracing implies sound energy travels along rays that are normal to all wave fronts [20]. The rays represent the sound energy and are equally distributed over the selected angle of sound propagation [24]. The rays disperse outward from the noise source and continue along a linear path until they strike a surface. The surface absorbs a percentage of the ray's energy corresponding to the assigned material absorption coefficient. The remaining energy is reflected in the room. A new "source" is created at the point of reflection with a total energy equal to that reflected in the room. This source emits a series of equally distributed rays back into the room. The process continues until approximately all sound energy has been absorbed by the surrounding surfaces. This procedure creates a diffuse sound field that accurately represents the propagation of noise in a space.

Materials found within the ODEON® materials library were assigned to each surface. Additional materials were added to the library for preliminary estimates of the absorption coefficients of steel, fibreglass and high-density polyethylene (HDPE). Absorption coefficients for steel were obtained from a paper by Sü and Caliskan [40]. They presented absorption coefficients for a steel door, which was considered to be sufficient for this model. A database provided by the Acoustic Project Company® was used to develop the fibreglass material file [8]. The 25mm fibreglass resin-bonded material was selected as the base point for the software's material file. A paper by Ersoy and El-Hafid provided estimates of the absorption coefficients for HDPE over a range of frequencies [12]. Values were taken from the plot in their paper for each octave band. Table 3.1 provides a list of all materials used in the model and to which surfaces they were assigned.

Table 3.1: Assigned materials in the ODEON® material list.

Material ID	Material Specification	Surface Types
101	Smooth unpainted concrete	Concrete floors
1000	Smooth brickwork with flush pointing, painted	Brick walls
3004	Wooden floor on joists	Wooden platform
3068	Plywood paneling, 1 cm thick	Walls, columns and ceilings
5000	Steel trapez profile	Facility roof
5001	Steel door [40]	Dumbwaiter door and steel beams
10007	Solid wooden doors	Wooden doors
12000	Mineral spray-on materials, 1.27cm mineral fibre	Insulated ceiling
12600	25mm fibreglass resin-bonded material [8]	Fibreglass tanks
15000	High density polyethylene [12]	HDPE tarps

Scattering coefficients were assigned to each surface based on its material and the layout of the room. The user manual for ODEON Industrial® provides scattering coefficients at the mid-range frequency for a series of different material types. Scattering coefficients were applied to the surfaces based on their similarity to the material types listed in the manual. Table 3.2 lists the scattering coefficients applied to each type of surface.

Table 3.2: Scattering coefficients assigned to surfaces in the model.

Surface	Scattering Coefficient [-]
Concrete floors (excluding First Feed room)	0.020
Dumbwaiter metal door	0.030
Metal roof	0.035
Wooden roof	0.035
Fibreglass tanks	0.050
Plywood walls	0.050
Plywood ceilings	0.050
Plywood columns	0.050
HDPE tarps	0.050
Wooden doors	0.050
First Feeding room concrete floor	0.100
Hatchery insulated roof	0.200
Wooden platform	0.600

Design of Experiments and numerical optimization

The Design of Experiment (DOE) methodology was applied to modify material absorption coefficients in each room. This was required to match the model's reverberation times with those measured at the facility. An outline of the testing procedure for the DOE methodology used in this research is presented below:

1. Determine general material properties for all major surfaces in each room.

2. Identify surfaces important for achieving accurate reverberation times.

3. Determine appropriate ranges of material absorption coefficients for each selected material.

4. Use a Latin hypercube design varying the absorption coefficient within its acceptable range to determine the relationship between absorption coefficient and reverberation time.

5. Use numerical optimization to determine the best combination of absorption coefficients to achieve the desired (measured) reverberation time in that room.

Each surface in the model was assigned a material that was deemed appropriate based on observations made at the facility. The materials initially assigned to the model were selected to provide a close starting point. However, they did not necessarily match the materials used in the construction of the facility, as this information was not known. Additionally, the simulation used a simplified model that did not include all objects found within each room. This approach was recommended by ODEON® [35]. Therefore, the absorption coefficients of materials in the room had to be modified to account for these differences.

A Latin hypercube design was selected to perform the DOE simulations as it was considered to be efficient and accurate for the optimization of material absorption coefficients [18][17]. Each room was considered to be a closed system, which allowed the reverberation times to be matched by room within the model. A Latin hypercube design was developed for each room and varied based on the number of factors included. The reverberation times differed over the octave bands; therefore, numerical optimization using DOE had to be performed for each octave in each room.

Experimental results were imported into Design-Expert® to analyze the data for numerical optimization. Either an inverse or inverse square root transformation was applied to each experiment based on the suggestion of the Box-Cox normality plot.

Three assumptions were made to perform the experiment; the normality of the residuals, the equality of variance and the independence of residuals. All three assumptions were validated before numerical optimization. Terms with a p-value of less than 0.05 were considered to be significant to the model. Other terms were included if they were required to maintain the hierarchy. Upper and lower limits were set for each absorption coefficient based on known absorption properties from similar materials. The coefficients were adjusted within their prescribed limits to converge on the measured reverberation time. The numerical optimizations of the absorption coefficients were then validated using the numerical simulations in ODEON Industrial® by comparing the measured and simulated reverberation times.

Sound Sources

The noise source sound power level measurements were analyzed using LabVIEW® in accordance with ISO 3746:2010. The noise sources were added to the ODEON® model as either a point source or a line source. A line source was applied for some ventilation systems and pipes containing running water. All other sources, such as generators, pumps and standpipes were modelled as point sources. The sound power levels were validated in the model using the SPLs captured in specific areas of the facility. This was achieved by placing receivers in these locations to measure the SPL. The sound power level of a source was adjusted, such that the simulated SPL at a receiver location matched the measured SPL at that spot.

Sound was permitted to travel through walls, floors and ceilings in the model to represent the transmission of noise throughout the facility accurately. Preliminary values of the sound transmission class (STC) of plywood was provided by American

Acoustical Products® [37]. The STC of 3/4 inch plywood was applied to all plywood walls, plywood ceilings, and wooden doors. The steel beams found on the ceiling of the Hatchery were assigned the STC of 25 gauge steel [27]. The STC of the concrete floors were initially assigned the properties of lightweight concrete blocks outlined in a paper by Zeitler et al. [43]. Modifications were made to the transmission coefficients using the simulated SPLs across rooms, making every effort to get simulated and measured SPLs to equal, further validating the model.

Assessment of the effectiveness of design solutions to mitigate noise levels

Engineering design solutions were tested once the model had been entirely validated. The design solutions were selected based on the results of the acoustic numerical simulation of the completed model, as well as observations made during the site visit. The solutions were tested using set receiver locations as well as a grid response. The grid consisted of a series of receivers placed one meter apart on selected surfaces. The observations made from the results of implementing the engineering design solutions in the model were used to determine the viability of applying these solutions on site.

3.3.4 Instrumentation

Experimental tests

A dodecahedron omnidirectional noise source Larson-Davies® BAS001 connected to a sound generator was used to generate pink noise for reverberation time measurements. Class-1 model 378B02 ICP handheld microphones by PCB Piezotronic® connected to a National Instruments® model 9234 BNC input card that was connected via

USB to a laptop computer was used to capture SPL decay in areas of the facility. The same equipment was used to measure sound levels in each room to validate the room acoustic parameters and determine the sound power levels of all identified noise sources. The microphone was calibrated to 94.0 dB each day before any measurements were taken using the Larson and Davies® calibrator model CAL200. Post-processing of data from the handheld microphones was performed using National Instrument's LabVIEW®.

Numerical Simulations

A 3D geometrical model of the facility was developed using SketchUp® and was exported into ODEON Room Acoustics Software Industrial® 15 to perform all acoustic numerical simulations. MathWorks MATLAB® R2017b was used to create design cases for optimizing material absorption coefficients, and this data was imported into StatEase Design-Expert® 11 for numerical optimization. The dimensions of the facility structure were provided by the facility management. Any missing dimensions were measured in situ with a laser distance measurer.

According to [21], we checked that the noise source was able to generate a noise level sufficiently greater than the background noise found in the room to develop the required sound decay curve.

3.4 Results

3.4.1 Determination of Reverberation Times

Figure 3.3 provides the source-microphone combinations used in each room to measure the reverberation times at the facility.

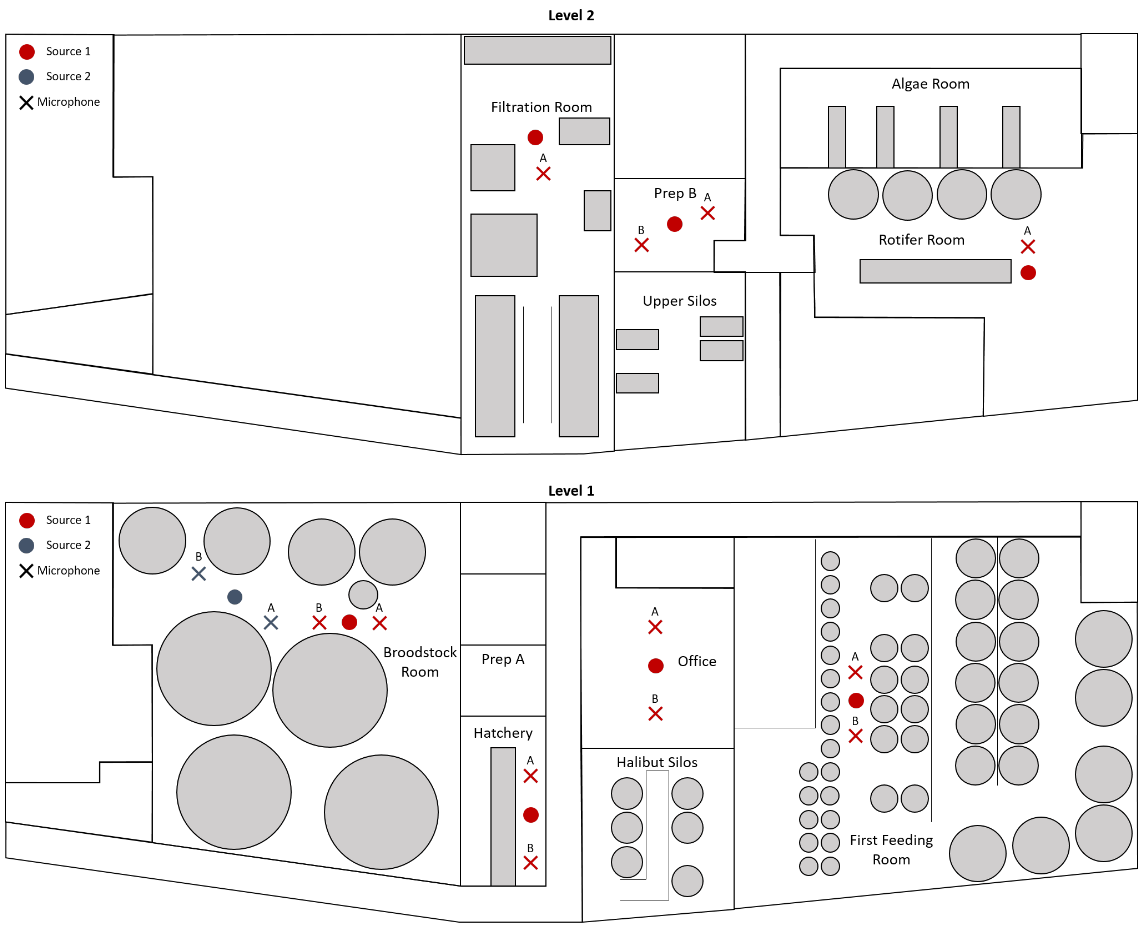


Figure 3.3: Source-microphone combinations used at the research facility.

The reverberation time in the Broodstock room was measured at two source-positions with four independent source-microphone combinations: two at source position one and two at source position two. Two measurements were taken for each source-microphone combination. The reverberation time for the room was calculated for each octave band and averaged over the four positions. All remaining rooms only used one source position. The Hatchery, Office, First Feeding room and Prep room B had microphones placed at two different locations, with two measurements taken at each position. The Filtration room and the Rotifer room had one microphone position, with two measurements taken for that source-microphone combination. The slopes of the measured decay curves were used to predict the reverberation times in each room. Not all decay curves displayed a 45 dB decay; however, this was expected, and reverberation times were estimated using the slopes available for each octave band. The decay curves are shown in Appendix B.

Table 3.3 provides the average reverberation times for the rooms in the facility using 1/1 octave bands. It is worth noting that the reverberation times at 8000 Hz for all rooms were considered to be inaccurate due to how little sound energy was present and reflected in that octave band.

Table 3.3: Reverberation times (T_{30}) measured at the research facility.

Frequency [Hz]	Broodstock [s]	Hatchery [s]	First Feeding [s]	Filtration [s]	Prep B [s]	Rotifer [s]
63	1.45	1.65	1.43	2.01	1.42	1.10
125	1.94	1.69	1.54	1.70	1.40	1.05
250	1.82	1.50	1.43	1.71	1.30	0.95
500	1.80	1.39	1.56	1.74	1.35	1.08
1000	1.96	1.25	1.68	1.78	1.30	1.01
2000	1.76	1.24	1.68	1.54	1.30	1.02
4000	1.85	1.36	1.58	2.02	1.36	1.04
8000	2.73	2.64	3.49	9.51	1.55	1.63

3.4.2 Numerical Optimization of Material Absorption Coefficients

The initial reverberation times calculated in the numerical model varied significantly from those measured at the facility. This was largely due to the materials and absorption coefficients assigned to the model. Numerical optimization of the absorption coefficients of select materials was performed to reduce the discrepancy between the measured and simulated reverberation times. The DOE methodology outlined in Section 3.3.2 was applied to perform this optimization. All Latin hypercube designs used for the absorption coefficients of each room can be found in Appendix C.

Broodstock Room

Within the Broodstock room, the absorption coefficients of four materials were modified using a Latin hypercube design. The plywood walls, the plywood ceiling, the fibreglass tanks and the HDPE tarp covers were all selected for the numerical optimization. The walls and ceiling had to account for the absorption of sound from all objects not modelled. The fibreglass tanks and HDPE tarp covers were also included, as it was highly likely that the material properties obtained from other papers may not be suitable for this model. The coefficients for the plywood walls and plywood roof were allowed to range from 0.00 to 0.50. The coefficients for the fibreglass tanks ranged from 0.00 to 0.40, while the coefficients for the HDPE tarp covers ranged from 0.00 to 0.30. Table 3.4 shows the optimized absorption coefficients of the four materials and the comparison between the measured and simulated reverberation times.

Table 3.4: Optimized absorption coefficients (α) for the Broodstock room.

Frequency [Hz]	Walls [-]	Ceiling [-]	Fibreglass [-]	HDPE [-]	Simulated T_{30} [s]	Measured T_{30} [s]
63	0.199	0.155	0.167	0.051	1.44	1.45
125	0.117	0.114	0.125	0.06	1.95	1.94
250	0.118	0.119	0.179	0.085	1.83	1.82
500	0.132	0.130	0.172	0.049	1.79	1.80
1000	0.115	0.113	0.149	0.086	1.97	1.96
2000	0.106	0.138	0.125	0.126	1.76	1.76
4000	0.078	0.047	0.071	0.115	1.85	1.85
8000	0.078	0.047	0.071	0.080	0.97	2.73

Hatchery

The absorption coefficients of two materials were modified in the Hatchery. The plywood walls and the insulated ceiling were included in the DOE numerical optimization to account for any discrepancies within the model. The Hatchery shared one of its walls with the Broodstock room. Therefore, the absorption coefficients of that wall were not modified in this stage of the optimization. Twenty different combinations of coefficients were developed using the Latin hypercube design. Table 3.5 provides the optimized coefficients for the plywood walls and the insulated ceiling in the Hatchery.

Table 3.5: Optimized absorption coefficients (α) for the Hatchery.

Frequency [Hz]	Walls [-]	Ceiling [-]	Simulated T_{30} [s]	Measured T_{30} [s]
63	0.061	0.039	1.66	1.65
125	0.073	0.072	1.68	1.69
250	0.089	0.083	1.51	1.50
500	0.095	0.083	1.39	1.39
1000	0.096	0.122	1.24	1.25
2000	0.111	0.096	1.24	1.24
4000	0.054	0.077	1.36	1.36
8000	0.054	0.077	0.84	2.64

Office

The Office consisted of two walls made of plywood and two brick walls. The brick walls were located on the east and south sides of the room. The absorption coefficients of both materials, along with the coefficients of the plywood ceiling, were modified in the experiment. All three factors ranged from 0.00 to 0.50 in the design. Table 3.6 contains the results of the experiment for the Office.

Table 3.6: Optimized absorption coefficients (α) for the Office.

Frequency [Hz]	Walls [-]	Ceiling [-]	Brick [-]	Simulated T_{30} [s]	Measured T_{30} [s]
63	0.165	0.140	0.036	1.41	1.39
125	0.182	0.158	0.039	1.27	1.26
250	0.195	0.177	0.043	1.16	1.16
500	0.207	0.191	0.039	1.06	1.06
1000	0.215	0.181	0.032	1.06	1.05
2000	0.210	0.173	0.044	1.04	1.04
4000	0.163	0.135	0.032	1.05	1.05
8000	0.030	0.030	0.015	1.09	1.08

First Feeding Room

Four materials were included in the experiment for the First Feeding room. The absorption coefficients of the plywood walls, plywood ceiling, fibreglass tanks, and HDPE curtains were all optimized to modify the reverberation time of the room. This room shared a brick wall with the Office. Therefore the optimized absorption coefficients for that wall found in Section 3.4.2 were applied in this experiment. The plywood wall and plywood ceiling coefficients ranged from 0.00 to 0.20. The coefficients for the fibreglass tanks ranged from 0.00 to 0.40, while those of the HDPE curtains ranged from 0.00 to 0.20. Table 3.7 shows the optimized coefficients and the accuracy of the simulated T_{30}.

Table 3.7: Optimized absorption coefficients (α) for the First Feeding room.

Frequency [Hz]	Walls [-]	Ceiling [-]	Fibreglass [-]	HDPE [-]	Simulated T_{30} [s]	Measured T_{30} [s]
63	0.050	0.073	0.072	0.012	1.43	1.43
125	0.045	0.045	0.072	0.044	1.54	1.54
250	0.070	0.052	0.086	0.013	1.42	1.43
500	0.050	0.040	0.073	0.025	1.54	1.56
1000	0.032	0.045	0.063	0.014	1.67	1.68
2000	0.065	0.045	0.045	0.020	1.69	1.68
4000	0.090	0.030	0.015	0.028	1.58	1.58
8000	0.090	0.030	0.015	0.028	0.87	3.49

Prep Room B

The absorption coefficients of the plywood walls and the plywood ceiling were the only two parameters included in the experiment for Prep room B. The coefficients for both materials ranged from 0.00 to 0.50. Table 3.8 contains the results of the numerical optimization for Prep room B.

Table 3.8: Optimized absorption coefficients (α) for Prep room B.

Frequency [Hz]	Walls [-]	Ceiling [-]	Simulated T_{30} [s]	Measured T_{30} [s]
63	0.095	0.063	1.43	1.42
125	0.088	0.083	1.41	1.40
250	0.101	0.085	1.30	1.30
500	0.094	0.080	1.36	1.35
1000	0.101	0.070	1.30	1.30
2000	0.095	0.065	1.30	1.30
4000	0.060	0.050	1.36	1.36
8000	0.060	0.050	0.83	1.55

Filtration Room

The absorption coefficients of the plywood wood walls and the plywood ceiling were modified for the Filtration room. One wall of the Filtration room was shared with Prep room B; therefore, this wall was not included in this analysis. Both factors were set to range from 0.00 to 0.50. Table 3.9 shows the results of the experiment.

Table 3.9: Optimized absorption coefficients (α) for the Filtration room.

Frequency [Hz]	Walls [-]	Ceiling [-]	Simulated T_{30} [s]	Measured T_{30} [s]
63	0.104	0.061	2.01	2.01
125	0.113	0.107	1.70	1.70
250	0.120	0.103	1.71	1.71
500	0.120	0.085	1.74	1.74
1000	0.130	0.080	1.77	1.78
2000	0.110	0.108	1.54	1.54
4000	0.080	0.080	1.42	2.02
8000	0.080	0.080	0.88	9.51

Rotifer Room

The Rotifer room was optimized by varying three parameters; the plywood walls, the plywood ceiling and the fibreglass tanks. All three factors had absorption coefficients that ranged from 0.00 to 0.50 in the Latin hypercube design. Table 3.10 provides the optimized combination of absorption coefficients to match the measured reverberation time in the room.

Table 3.10: Optimized absorption coefficients (α) for the Rotifer room.

Frequency [Hz]	Walls [-]	Ceiling [-]	Fibreglass [-]	Simulated T_{30} [s]	Measured T_{30} [s]
63	0.185	0.163	0.025	1.10	1.10
125	0.265	0.104	0.077	1.04	1.05
250	0.167	0.197	0.151	0.94	0.95
500	0.136	0.162	0.132	1.09	1.08
1000	0.150	0.115	0.400	1.01	1.01
2000	0.156	0.121	0.236	1.02	1.02
4000	0.117	0.127	0.068	1.05	1.04
8000	0.117	0.127	0.068	0.71	1.63

3.4.3 Sound Power Level Measurements

Sound power levels were measured for all identified sources at the facility. Thirteen sources were identified in total across the facility; one in the Algae room, two in the Rotifer room, two in the Filtration room, three in the First Feeding room, one in the Halibut Silos, one in the Hatchery and three in the Broodstock room. Figure 3.4 shows the location of each noise source. The sources are labelled the same as they were in the numerical model.

The source in the Algae room was the ventilation system in the room. The source was modelled as a line source since the ventilation system spanned the entire length of the room. A Lambert radiation type was selected for the line source to model the strength of the emitted rays accurately.

Both sources in the Rotifer room were modelled as point sources. The first source was a mechanical feeding mechanism resting on the table. The second source was free-flowing water into a drain on the floor. The feeding mechanism was considered to be an omnidirectional source, while the flowing water was semi-directional. This was because this noise source was located on the lower boundary, and sound could

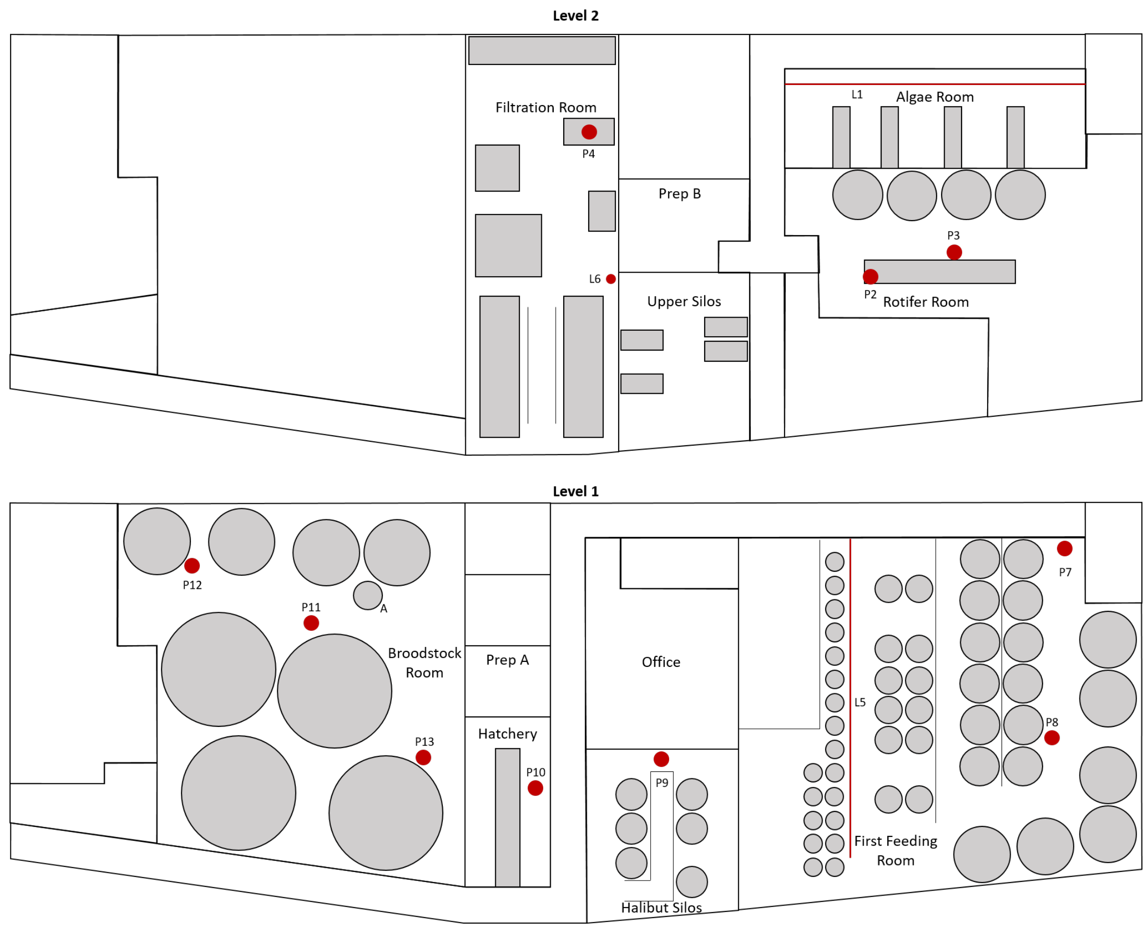


Figure 3.4: Position of noise sources in the research facility. Each dot or line represents a noise source. "P" denotes a point source. "L" denotes a line source. The list of noise sources is shown in Table 3.11.

only be transmitted back into the room.

The first source in the Filtration room corresponded to the turbine and compressor and was modelled as an omnidirectional point source. The second source located in this room was a pipe carrying water up the east wall. This pipe was modelled as a line source with an assigned Lambert radiation type.

A pipe carrying water across the ceiling was identified as the first noise source in the First Feeding room. This source was modelled as a line source with a Lambert radiation type. The other two sources were a vent hanging from the ceiling and a standpipe next to a fibreglass tank. Both of these sources were modelled as point sources with semi-directional sound profiles.

The noise source in the Halibut Silos was another vent hanging from the ceiling. It was modelled as a point source with a semi-directional sound profile.

The Hatchery had one noise source associated with water flowing into a small tank. This source was modelled as an omnidirectional point source.

All three sources in the broodstock room were considered to be point sources. The first source represented water flowing into a drain on the floor. The other two sources were both standpipes associated with the nearby fibreglass tanks. All three noise sources were considered to be semi-directional due to the surrounding boundaries.

The sound power level for each source was measured following the procedure outlined in Section 3.3.2. Corrections were made for the environmental conditions using equation A.1 in ISO 3746:2010. Table 3.11 provides the corrected sound power level of each octave band for all of the noise sources.

3.4.4 Modification of Material Transmission Data

Certain walls were selected in the model to allow for noise transmission. The Filtration room was found to produce the highest noise levels across the entire facility; therefore, sound was permitted to travel into adjacent rooms. The shared walls of the Filtration room with the Broodstock room and Prep room B, along with the floor of the Filtration room and the ceilings of both the Hatchery and the Office, were all

Table 3.11: Sound power levels (L_W) for noise sources at the research facility.

Noise source	Label	L_W at each octave band [dB]							
		63	125	250	500	1000	2000	4000	8000
Algae Vent	L1	74.3	74.2	71.4	68.9	68.7	65.9	63.2	56.6
Rotifer Feeding Mech	P2	64.8	70.8	69.1	68.1	65.0	67.6	67.8	64.4
Rotifer Water Flow	P3	69.5	74.7	73.7	68.6	65.7	64.0	64.0	60.3
Filtration Turbine	P4	75.8	78.2	83.3	87.2	84.3	76.7	72.9	72.1
First Feeding Pipe	L5	64.5	63.8	66.2	68.0	68.4	69.1	66.7	64.3
Filtration Pipes	L6	81.8	78.5	79.9	82.1	83.3	80.9	77.7	75.7
First Feeding Vent	P7	85.3	81.2	73.7	69.3	69.7	66.7	63.4	58.6
Filtration Standpipe	P8	69.2	70.9	69.4	71.7	73.8	72.9	70.6	67.1
Halibut Silos Vent	P9	85.3	81.2	73.7	69.3	69.7	66.7	63.4	58.6
Hatchery Water Flow	P10	69.5	74.7	73.7	68.6	65.7	64.0	64.0	60.3
Broodstock Water Flow	P11	69.5	74.7	73.7	68.6	65.7	64.0	64.0	64.0
Broodstock Standpipe 1	P12	67.4	73.3	68.5	68.2	69.7	70.2	69.0	66.6
Broodstock Standpipe 2	P13	69.2	70.9	69.4	71.7	73.8	72.9	70.6	67.1

set to transmission type surfaces. In addition to this, the shared wall between the Broodstock room and the Hatchery was allowed to transmit noise.

The transmission data of the plywood walls were initially assigned the transmission properties of 3/4" plywood provided by American Acoustical Products®. Simulations were performed to modify the transmission properties of the walls using the SPL measurements taken at known locations in both the Broodstock room and Prep room B. The same transmission data was then applied to the wooden doors of the Filtration room.

The concrete floor in the Filtration room was assigned the transmission data of lightweight concrete blocks outlined by Zeitler et al. The ceilings of Prep room A and the Office were made of plywood. They were therefore assigned the transmission data found in the previous step. The reduction indexes of the concrete floor were modified using a similar approach with the known SPL measurements taken in Prep room A and the Office.

The wall between the Hatchery and the Broodstock room was also made of plywood and was assigned the same transmission data as all other plywood surfaces. The ceiling of the Hatchery, however, consisted of steel beams covered in mineral wool. The transmission data for 25 gauge steel provided by MECART® was applied to the steel beams and modified using the SPL measurements taken in the Hatchery.

Table 3.12 provides the transmission data applied to the selected surfaces. Note that this table only provides the reduction indexes for the center bands. The 1/3 octave sidebands were given the same indexes as their center band.

Table 3.12: Reduction indexes for the materials selected for sound transmission.

Surface Name	Reduction index at each octave band [dB]							
	63	125	250	500	1000	2000	4000	8000
Plywood Walls	10.0	10.0	12.5	12.5	15.0	15.0	17.5	17.5
Plywood Ceiling	10.0	10.0	12.5	12.5	15.0	15.0	17.5	17.5
Wooden Doors	10.0	10.0	12.5	12.5	15.0	15.0	17.5	17.5
Concrete Floor	12.5	12.5	15.0	15.0	20.0	20.0	25.0	25.0
Insulated Ceiling	12.5	12.0	15.0	22.0	27.5	32.0	40.0	40.0

3.4.5 Model Validation

The model was validated at three stages. The absorption coefficients found during the numerical optimization experiment were validated using confirmation runs of the acoustic simulation. The results presented in Section 3.4.2 showed that with the optimized absorption coefficients, the simulated reverberation times of each room fell within an acceptable range of 2% of the measured values for all low to midrange octave bands.

The second stage of model validation occurred after determining the sound power levels of each noise source. The sources were added to the model and simulations were performed to measure the SPL at specific locations. Receivers were placed at locations throughout the model where SPL measurements had been taken at the facility. The simulated SPL(A)s were then compared to the measured at SPL(A)s at each location. Table 3.13 shows the comparison of the simulated and measured SPL(A)s at each receiver. All SPL results from the model were found to agree with those taken at the facility within an acceptable range of 6%, indicating the sound power levels of the noise sources were determined correctly.

Table 3.13: Noise source sound power level (L_W) validation using measured SPL.

Receiver ID	Simulated SPL(A) [dB(A)]	Measured SPL(A) [dB(A)]
Algae 1	60.0	59.9
Algae 2	60.2	56.9
Rotifer 1	66.3	64.6
Rotifer 2	66.1	63.3
Filtration 1	82.4	83.3
Filtration 2	83.4	84.1
Filtration 3	80.6	81.9
Prep B 1	72.0	74.6
First Feeding 1	68.3	67.8
First Feeding 2	67.9	66.0
First Feeding 3	71.0	71.3
Halibut Silos 1	65.2	66.0
Halibut Silos 2	67.1	66.3
Hatchery 1	65.0	65.0
Hatchery 2	66.0	65.9
Hatchery 3	66.0	65.2
Broodstock 1	66.7	67.4
Broodstock 2	68.5	69.2
Broodstock 3	64.7	67.9
Broodstock 4	71.5	71.2

The final stage of model validation was related to the transmission properties of the selected surfaces. Additional SPL measurements taken at the facility were used to validate the reduction indexes of these materials. SPL measurements taken in the

Office, the Hatchery, the Broodstock room, Prep room B and Prep room A were all compared to the simulated SPLs to validate the transmission data of the surrounding surfaces. In addition to the measurement taken in Prep room B shown above, a second measurement was taken with the door closed between the Filtration room and Prep room B. Since there was no source located in Prep room B, all sound captured in that room had to be a result of sound transmission. This provided validation for the reduction indexes used for the plywood walls, plywood ceiling and wooden doors. The Office and Prep room A also did not contain any noise sources; therefore, all noise measured in these rooms had to come from sound transmission. The transmission data of the concrete floors was validated by matching the simulated SPL(A) to that measured in each room. Finally, the transmission data of the insulated ceiling in the Hatchery was validated using the SPL measurements taken in the Hatchery. The reduction indexes were adjusted such that the discrepancy between the simulated and measured SPL(A)s was minimal. Table 3.14 shows the comparison between the simulated and measured SPL(A)s for each receiver with the transmission loss data applied.

Table 3.14: Model validation with transmission loss data applied using measured SPL(A).

Receiver ID	Simulated SPL(A) [dB(A)]	Measured SPL(A) [dB(A)]
Office 1	52.4	53.2
Prep A 1	57.3	59.1
Prep B 2	66.1	66.8
Hatchery 1	64.9	65.0
Hatchery 2	65.9	65.9
Hatchery 3	65.8	65.2
Broodstock 1	67.4	67.4
Broodstock 2	69.1	69.2
Broodstock 3	65.8	67.9
Broodstock 4	71.7	71.2

The completed model, with all noise sources and receivers, is presented in Figure 3.5.

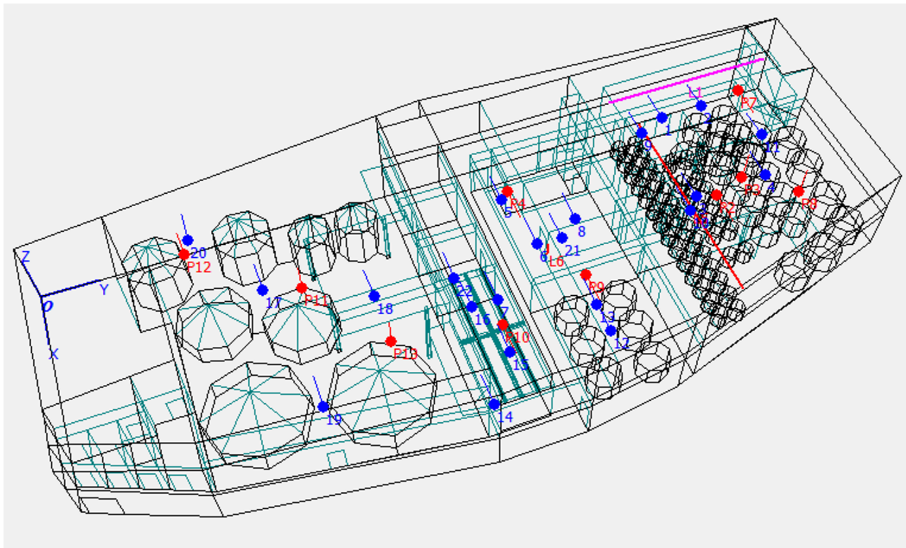


Figure 3.5: Validated numerical model of the research facility. Noise sources are denoted by red or magenta points and lines. Receiver locations are denoted by blue points in the model.

A grid of receivers was applied to the model to map the noise throughout the entire facility. The grid had receivers set 1.00 meter apart, and at a vertical distance of 1.20 meters above all selected surfaces. The noise map is shown in Figure 3.6. A-weighted sound pressure levels were categorized as either safe, potentially hazardous, or hazardous for employees based on the measured exposure level. Safe SPL(A)s were categorized as any noise measurements below 75.0 dB(A). Potentially hazardous SPL(A)s were identified as any measurements taken between 75.0 and 85.0 dB(A). SPL(A)s of 85.0 dB(A) and above were deemed hazardous for employees and were marked as areas of concern at the facility. The range for hazardous SPL(A)s was set following recommendations by the ACGIH for noise exposure threshold limit values over an eight-hour workday. Potentially hazardous noise levels were given the range of 75.0 to 85.0 dB(A), as it has been shown that extended exposure to levels above 75.0 dB(A) can result in hearing impairment [36]. As seen in the noise map, A-weighted sound pressure levels were highest within the Filtration room close to the machinery producing loud noise. SPL(A)s in the adjacent rooms were also approaching potentially hazardous levels due to noise leaving the Filtration room.

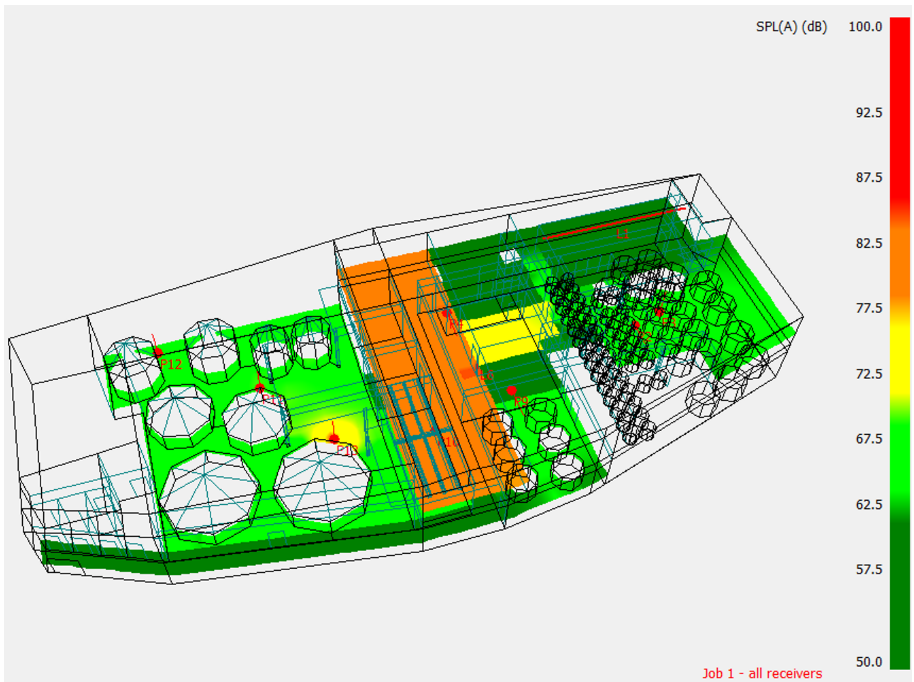


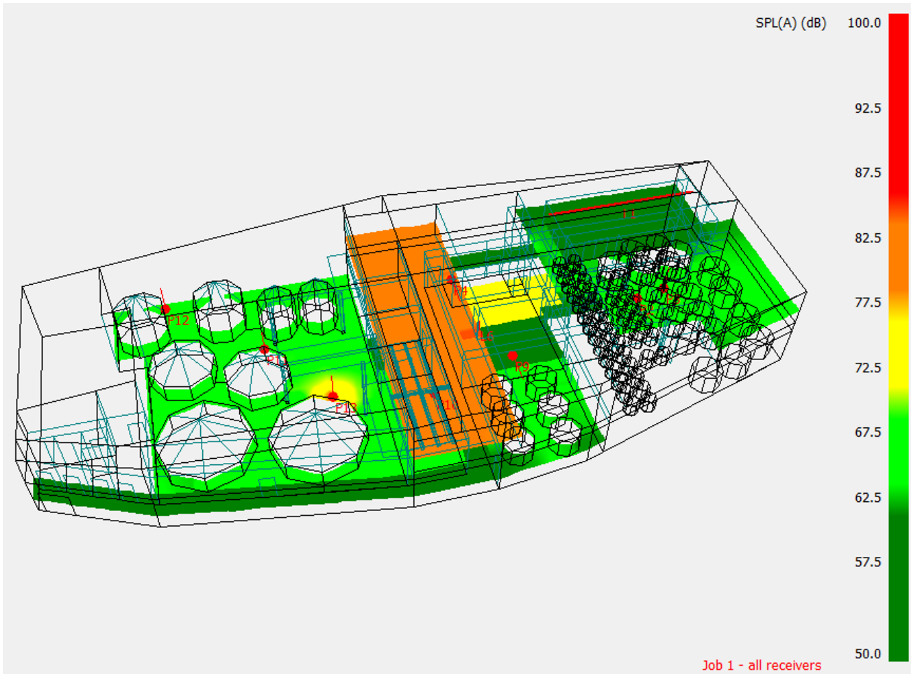
Figure 3.6: Noise map for the validated model of the research facility.

3.4.6 Assessment of feasible and practical solutions to mitigate noise levels

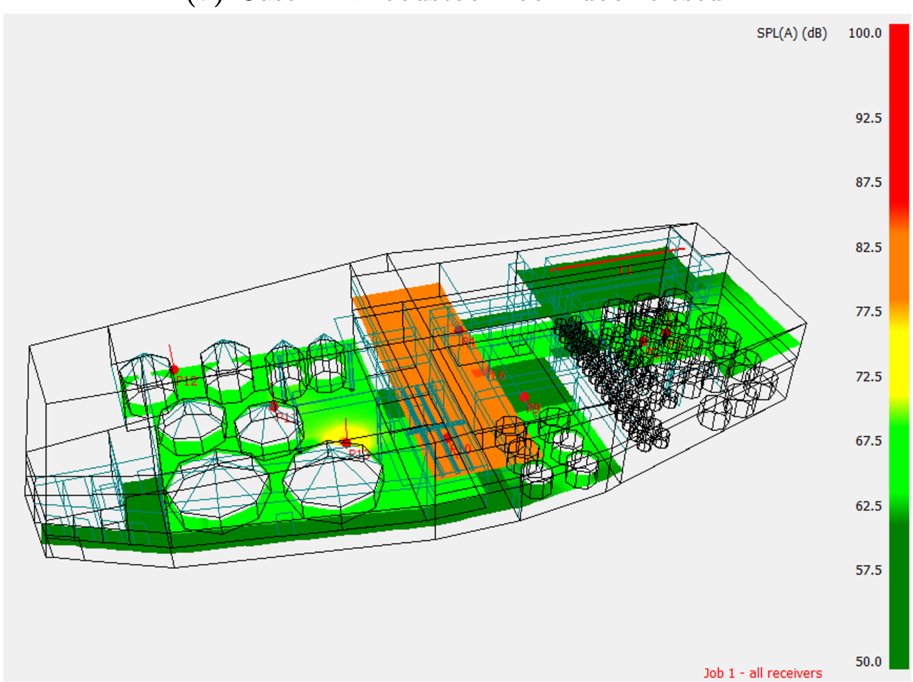
Engineering design solutions were assessed for the facility based on the propagation of noise seen in the simulated noise map. As stated above, the highest noise levels can be found in the Filtration room, and sound tends to transmit to nearby rooms. During the noise surveys, it was noticed on site that doors leading into the Filtration room from both Prep room B and the Broodstock room were always held open, allowing sound to escape this room easily. Therefore, the first design solution tested was to close the entryways into the Filtration room. This was performed by changing the material properties of the doorways from completely transparent to a wooden door. The transmission data of wooden doors was also applied to the two surfaces. Three different combinations were tested to observe the overall effect of these solutions to reduce sound transmission. The first test case (Case 1) involved only closing the door between the Filtration room and the Broodstock room. The second (Case 2) had that doorway remain open, but closed the one between the Filtration room and Prep room B. The third (Case 3) had both doorways closed off. Table 3.15 compares the SPL(A)s at receiver locations within each of the three rooms to show the effect of implementing this design solution. The original model represents the facility at normal operating conditions with no design solutions applied. The noise maps of the three scenarios are presented in Figure 3.7. This shows that closing off any openings for sound to travel out of the room can reduce noise levels within the surrounding areas by upwards of 6 dB without increasing the noise levels in the Filtration room.

Table 3.15: Effectiveness of closing off doorways leading to the Filtration room on reducing SPL(A).

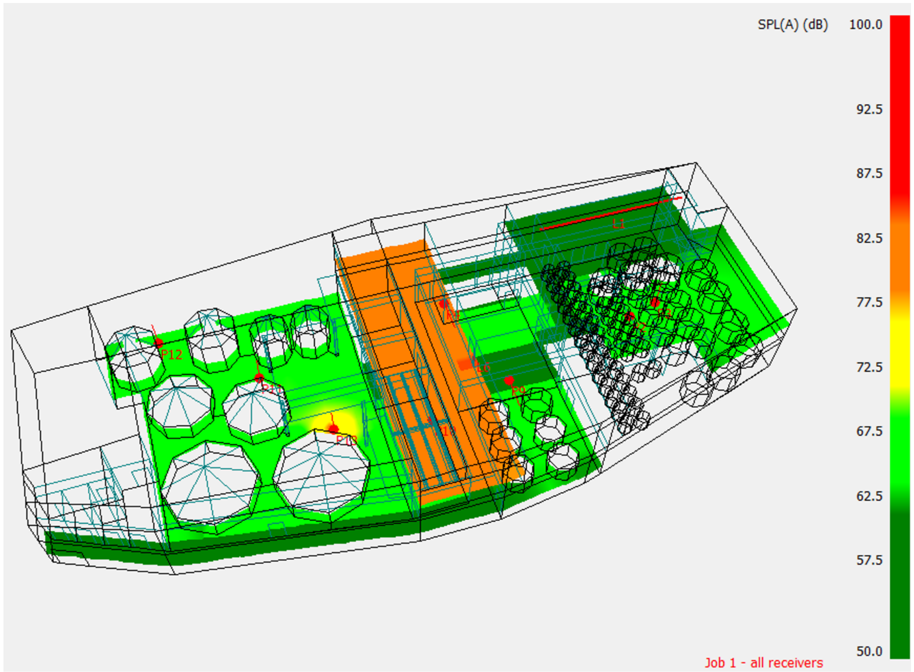
Receiver ID	Original Model [dB(A)]	Case 1 [dB(A)]	Case 2 [dB(A)]	Case 3 [dB(A)]
Filtration 1	82.4	82.2	82.0	82.2
Filtration 2	83.4	82.9	83.2	83.2
Filtration 3	80.6	80.0	80.1	80.1
Prep B 1	72.0	73.1	65.2	65.8
Broodstock 1	67.4	66.6	67.5	66.6
Broodstock 2	69.1	68.5	69.2	68.6
Broodstock 3	65.8	64.8	66.0	65.3
Broodstock 4	71.7	71.4	71.7	71.5



(a) Case 1 - Broodstock room door closed.



(b) Case 2 - Prep room B door closed.



(c) Case 3 - Both doors closed.

Figure 3.7: Noise maps of the research facility testing the first three design solutions.

Another engineering design solution was tested to reduce the transmission of noise from the Filtration room. This design solution placed mineral wool over the plywood walls surrounding the Filtration room to prevent sound from escaping (Case 4). It was also selected to help reduce noise levels within the Filtration room. The simulations using the mineral wool were performed with both entrance ways closed as it was determined in the previous step that this was effective and did not hinder any operations on site. Mineral wool was selected as the insulation material, and the absorption properties were imported into ODEON®. The material properties of mineral wool were obtained from a material brochure [38]. Figure 3.8 shows the propagation of sound through the facility after adding the mineral wool to all of the walls in the Filtration room.

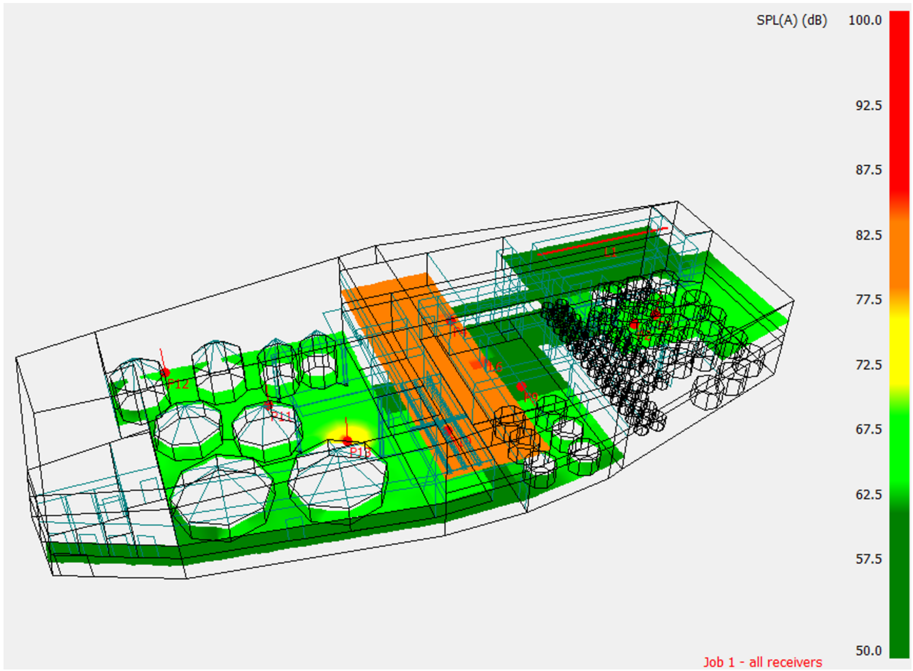


Figure 3.8: Noise map of the research facility with Case 4 - mineral wool insulation added around the Filtration room walls - applied.

The last engineering design solution tested for this model was to add insulating material to the ceiling of the Office (Case 5). While noise levels were well below the allowable limits in this room, it was found during the analysis of the SPLs that the majority of the sound energy transmitted into the room was within the low to midrange frequencies. Sound produced in these frequencies creates a constant hum in the background that could be disruptive to employee workflow. The same mineral wool material applied in the Filtration room was applied to the ceiling of the Office. Simulations were performed using both a grid of receivers and an individual receiver located in the center of the room. Figure 3.9 shows the reduction in SPL(A) over the octave bands of concern.

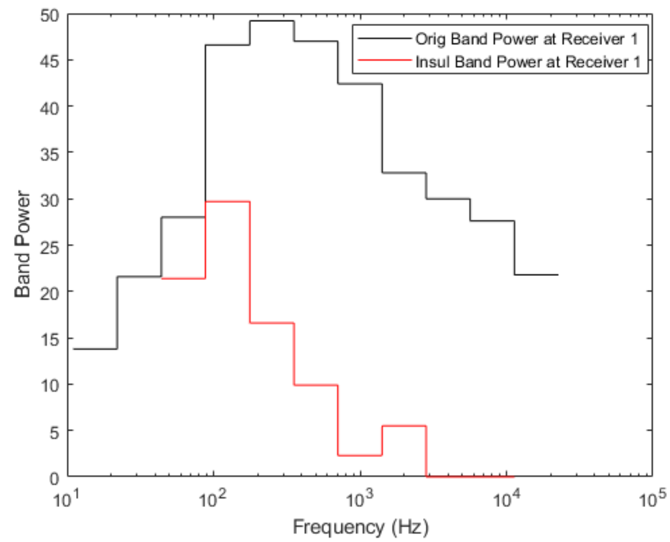


Figure 3.9: Band power plot of noise measured in the Office before and after mineral wool insulation is added to the ceiling.

Table 3.16 compares the SPL(A)s within the Filtration room, Office, and surrounding areas before and after the mineral wool had been applied to the model. SPLs in Prep room B decreased by more than 10 dB(A) during Case 4. In Case 5, the single receiver in the Office measured an SPL(A) of 30.5 dB(A), which was over 20 dB lower than what was measured without the insulation installed.

Table 3.16: Effectiveness of lining the Filtration room walls (Case 4) and Office ceiling (Case 5) with mineral wool in reducing SPL(A).

Receiver ID	Original Model [dB(A)]	Case 4 [dB(A)]	Case 5 [dB(A)]
Filtration 1	82.4	81.9	81.7
Filtration 2	83.4	83.3	83.1
Filtration 3	80.6	80.4	80.2
Prep B 1	72.0	58.4	65.6
Broodstock 1	67.4	65.3	66.5
Broodstock 2	69.1	67.8	68.7
Broodstock 3	65.8	63.1	64.8
Broodstock 4	71.7	71.2	71.5
Office 1	52.4	53.6	30.5

3.5 Discussion

The results from the noise surveys shows that noise was prevalent in the Filtration room, where large pieces of machinery were continually operating (Table 3.14). The noise measured in this room was close to 85dB(A). The facility manager had identified risk of noise exposure in this room (section 2.4.2) and hearing protection was provided to all employees to be worn while working in this room. The issue arose, however, when studying noise levels in adjacent rooms. Sound was easily transmitted from the Filtration room across the facility, into both of the Prep rooms, the Broodstock room, the Hatchery and the Office. These five rooms were noted as high traffic areas, and excessive noise in the rooms could cause hazardous working conditions for all site employees. Significant amounts of noise were found to transmit from the Filtration room into Prep room B, mainly because the employees often left the Filtration room door open all day. This also proved to be a problem in the Broodstock room. There was a doorway leading from the Filtration room to the Broodstock room that was always pinned open. Additionally, noise was able to transmit easily through the plywood walls, adding to the noise levels in both rooms. While the Office did not see significant noise levels transmitted from the Filtration room, noise within the low and midrange frequencies was prevalent and disturbed the working conditions of employees. These areas had to be addressed to try to reduce the risk of NIHL and improve the ergonomic conditions at the facility.

The numerical acoustic simulations of the facility required the input of many unknown parameters. While the reverberation times were known, little could be done using the databases provided to replicate the facility's exact acoustic properties, e.g. the absorption coefficient α, due to the complexity of the facility and the limitations of the software. The DOE methodology allowed these unknown parameters to be estimated and optimized, such that the model's reverberation times were in agreement with those measured on site. It also allowed for the selection of parameters to be validated through confirmation runs, where applying the optimized coefficients in the model returned expected reverberation times across all octave bands. The Latin hypercube design was found to be adequate for performing this experiment. It was extremely efficient, providing accurate results while minimizing the required number of runs.

The engineering design solutions applied to the model were all selected based on the known design and material make-up of the facility, along with the daily operating conditions employed. The two doors connected to the Filtration room were left open throughout the entire day, aiding sound to escape into adjacent rooms. The doorway into Prep room B from the hall remained open at all times due to the potential build-up of fumes in the room. This further contributed to the transmission of noise throughout the building. However, there was no operational or safety-related reason as to why either door leading to the Filtration room had to remain open. Therefore, the preliminary design solution was to close both of these doors. Doing so reduced SPL(A)s of approximately 6 dB in Prep room B and upwards of 1 dB in the Broodstock room. This modification is easy to implement at the facility and can significantly improve the working conditions in other areas of the building. The other two design solutions focused on structural changes that could be implemented to reduce noise transmission further. The addition of 3" acoustical insulation inside the walls of the Filtration room reduced the transmitted noise drastically to nearby rooms, with the most significant effect seen in Prep room B as there were no other active noise sources in that room. SPL(A)s in Prep room B decreased to 58.4 dB(A) with the door closed and the acoustic insulation installed. Applying the same insulation in the Office ceiling reduced the SPL(A) by over 20 dB in the room. This small change was also able to remove a significant portion of the low and midrange frequency noise that had been very disruptive to workers. These two design solutions are much more challenging to implement, but can have a significant effect on reducing sound transmission throughout the facility and inherently reduce the risk of excessive noise exposure for workers.

The use of standpipe covers suggested by Barnes et al. [3] will farther reduce noise levels in the Broodstock and First Feeding rooms.

3.5.1 Conclusion

In this paper, we presented the results from numerical simulations of acoustic propagation in a research facility of the aquaculture industry. In order to overcome the typical lack of information on the primary acoustic parameters of the facility, we used a DOE methodology. The results of the numerical simulations were validated against experimental measurements, and the results showed that applying DOE will improve the accuracy and efficiency of the numerical simulations. The model was then used to evaluate the effectiveness of practical solutions to mitigate noise propagation in the facility.

This procedure is not limited to aquaculture research facilities. The same engineering approach can be implemented in the design or operational stages of any indoor aquaculture facility. Numerical simulations modelling an aquaculture facility can provide valuable information on the source of high noise levels and its transmission throughout the facility. The numerical model allows for engineering design solutions to be tested without having to make significant modifications to the facility without knowing its effect on sound transmission. By testing and comparing design solutions in the numerical model, the optimal design solution can be selected to provide the safest work environment possible for the employees.

Chapter 4

Summary and Future Work

4.1 Summary

This research assessed the causes and severity of excessive noise in aquaculture in different industry sectors, applying multiple noise assessment techniques. Noise level measurements were taken throughout each facility to develop noise maps, an essential tool for evaluating the transmission of noise on site and determining areas where noise levels may be hazardous. Documenting the major noise sources and their sound power levels in these hazardous areas provided useful information on the excessive noise exposure risk level of employees and any commonalities observed across the aquaculture branches, identifying areas of interventions to mitigate noise. In consultation with the developed noise maps from the four facilities, it was determined that the hatchery, research facility, and laboratory were relatively safe work environments with respect to noise levels. However, these three facilities did have some areas that were considered potentially hazardous due to the common major noise sources present. Noise levels at the salmon farm were much more severe, due largely in part to the type of machinery used and the reduced size of the vessels.

Personal noise exposure was captured for each employee at the four facilities to understand the impact of noise in aquaculture further. In general, employees who occupied managerial roles were subjected to significantly less noise and were well below hazardous noise exposure levels. Their daily tasks mainly consisted of office work in areas far from the hazardous noise sources identified on site. The site manager of the salmon farm was an exception. He often accompanied the labourers during their tasks and often worked alongside noisy machinery due to the nature of the site. The labourers were exposed to higher noise levels at all sites as they were tasked with fish care and site maintenance, either using or working in the vicinity of the major noise sources daily. While only the labourers at the salmon farm were at a significant risk of excessive noise exposure, the others were still subjected to potentially hazardous levels, and caution should be taken when working in the hazardous areas.

After developing the noise maps and obtaining the personal noise exposures of employees, the next stage of understanding noise in aquaculture was to determine how noise propagated through a facility and what measures could be taken to reduce the risk of high exposure. Within the research facility, most of the noise emanated from the Filtration Room and spread to all nearby rooms. Using DOE, an accurate numerical model of the facility was created to display the transmission of noise to the high traffic areas and attempt to identify the primary sources of excessive noise. The engineering design solutions applied to the model all attempted to contain the sound near its source and greatly succeeded in reducing noise levels in nearby rooms by 10 dB. This procedure is not limited to research facilities; it can be applied in any aquaculture facility to provide a practical approach to reducing noise transmission and improving overall site safety.

4.2 Limitations

There are some limitations related to the research presented in this thesis. This research focused primarily on noise in the finfish sector of aquaculture. It did not include any sites from the shellfish sector, such as muscle or oyster farms. It also did not include other types of facilities involved in aquaculture, such as processing plants. Additionally, the data presented in this thesis may not represent the aquaculture industry as a whole. Only one site was selected to represent each type of facility included in the research. Both of these limitations are a result of a lack of response or interest in participation from the aquaculture industry. However, it can be concluded that facilities of similar operations and design of the ones included in this research would likely have similar noise levels and noise exposure risks.

4.3 Recommendations for Future Work

This research introduces many new findings and novel noise assessment procedures within aquaculture; however, it is not entirely comprehensive. The following topics are recommended for future work to further expand on the outcomes of this research:

1. The current research focused primarily on salmonids within the finfish sector of aquaculture. Further work should be performed to include other types of finfish facilities that rear cod or trout.

2. Additional facilities, including types that were not presented in this work, such as aquaculture processing plants, should be assessed for excessive noise to develop a more comprehensive representation of the industry.

3. The study should be expanded beyond finfish to include the shellfish sector as there is currently no literature available on noise in this branch of aquaculture.

4. A study on cost-effectiveness of different noise management techniques should be performed to determine the feasability of implementing each proposed solution.

5. Finally, the numerical procedure presented in this work should be extended to include other facilities, and the design solutions should be implemented to actually mitigate occupational noise exposures of aquaculture workers.

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Appendix A

ICEHR Ethics Approval

MEMORIAL UNIVERSITY

Interdisciplinary Committee on
Ethics in Human Research (ICEHR)

St. John's, NL Canada A1C 5S7
Tel: 709 864-2561 icehr@mun.ca
www.mun.ca/research/ethics/humans/icehr

ICEHR Number:	**20192681-EN**
Approval Period:	March 1, 2019 – March 31, 2020
Funding Source:	OFI (RGCS: 20181253; PI: Neis)
Responsible Faculty:	Dr. Lorenzo Moro Faculty of Engineering and Applied Science
Title of Project:	*Noise Exposure of Workers in the Aquaculture Industry of Newfoundland*

March 1, 2019

Dr. Lorenzo Moro
Department of Ocean and Naval Architectural Engineering
Faculty of Engineering and Applied Science
Memorial University of Newfoundland

Dear Dr. Moro:

Thank you for your correspondence of February 26, 2019 addressing the issues raised by the Interdisciplinary Committee on Ethics in Human Research (ICEHR) concerning the above-named research project. ICEHR has re-examined the proposal with the clarification and revisions submitted, and is satisfied that the concerns raised by the Committee have been adequately addressed. In accordance with the *Tri-Council Policy Statement on Ethical Conduct for Research Involving Humans (TCPS2)*, the project has been granted *full ethics clearance* to March 31, 2020. ICEHR approval applies to the ethical acceptability of the research, as per Article 6.3 of the *TCPS2*. Researchers are responsible for adherence to any other relevant University policies and/or funded or non-funded agreements that may be associated with the project.

The *TCPS2* **requires** that you submit an Annual Update to ICEHR before March 31, 2020. If you plan to continue the project, you need to request renewal of your ethics clearance and include a brief summary on the progress of your research. When the project no longer involves contact with human participants, is completed and/or terminated, you are required to provide an annual update with a brief final summary and your file will be closed. If you need to make changes during the project which may raise ethical concerns, you must submit an Amendment Request with a description of these changes for the Committee's consideration prior to implementation. If funding is obtained subsequent to approval, you must submit a Funding and/or Partner Change Request to ICEHR before this clearance can be linked to your award.

All post-approval event forms noted above can be submitted from your Researcher Portal account by clicking the *Applications: Post-Review* link on your Portal homepage. We wish you success with your research.

Yours sincerely,

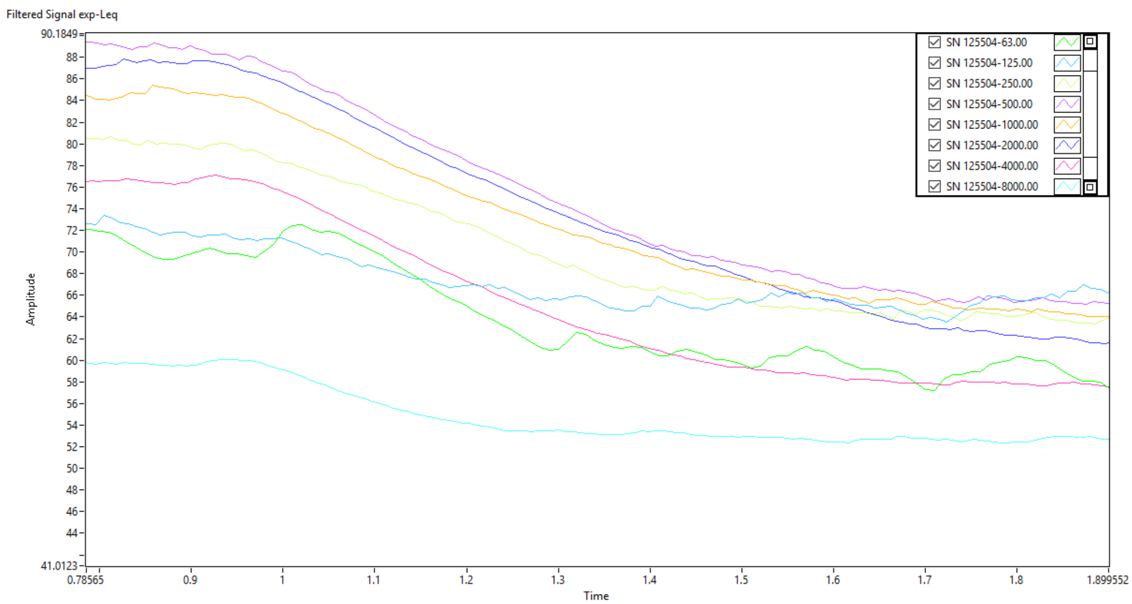
Kelly Blidook, Ph.D.
Vice-Chair, Interdisciplinary Committee on
Ethics in Human Research

KB/lw

cc: Director, Research Grant and Contract Services

Appendix B

Reverberation Decay Curves



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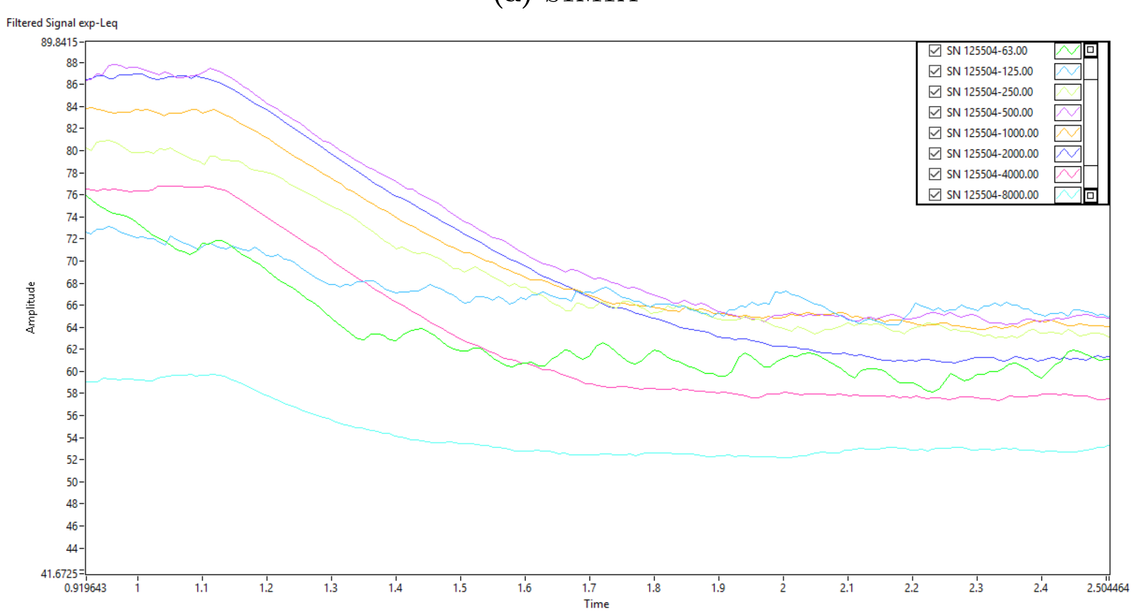

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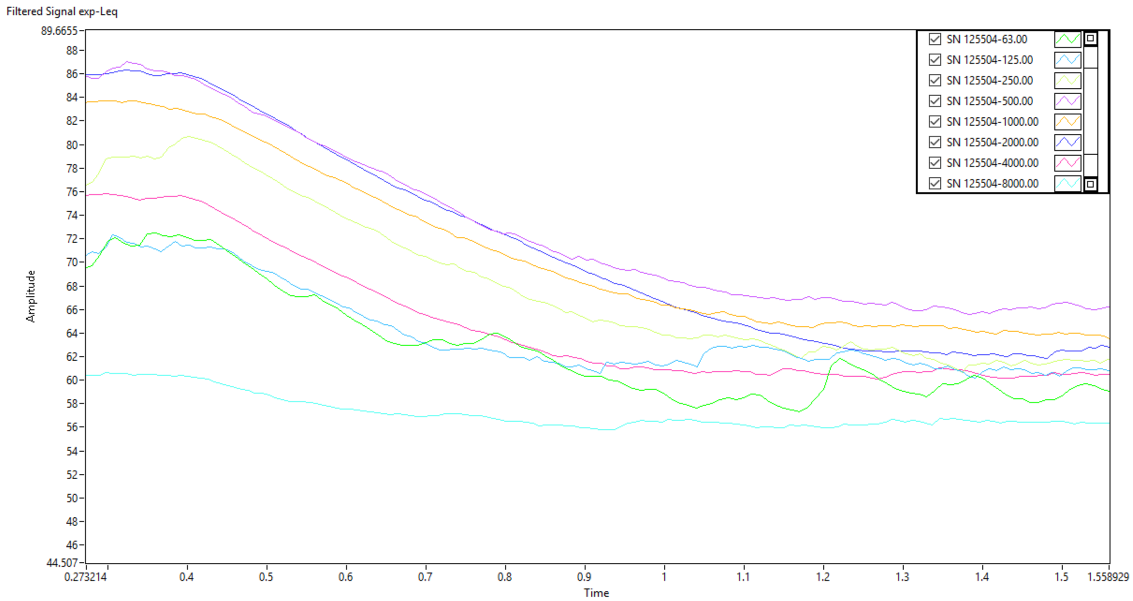

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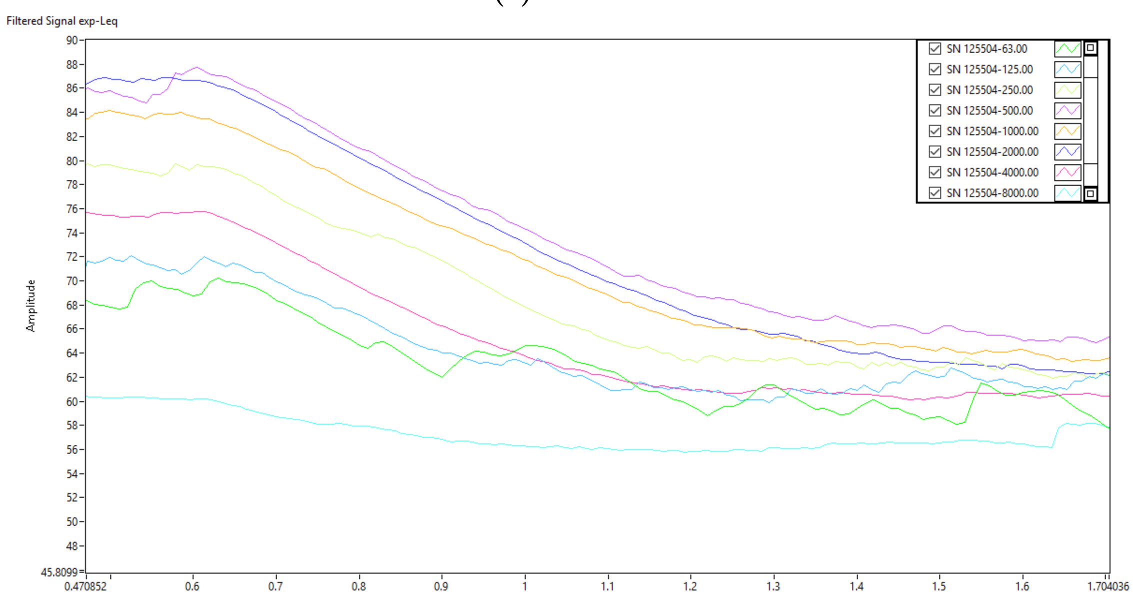

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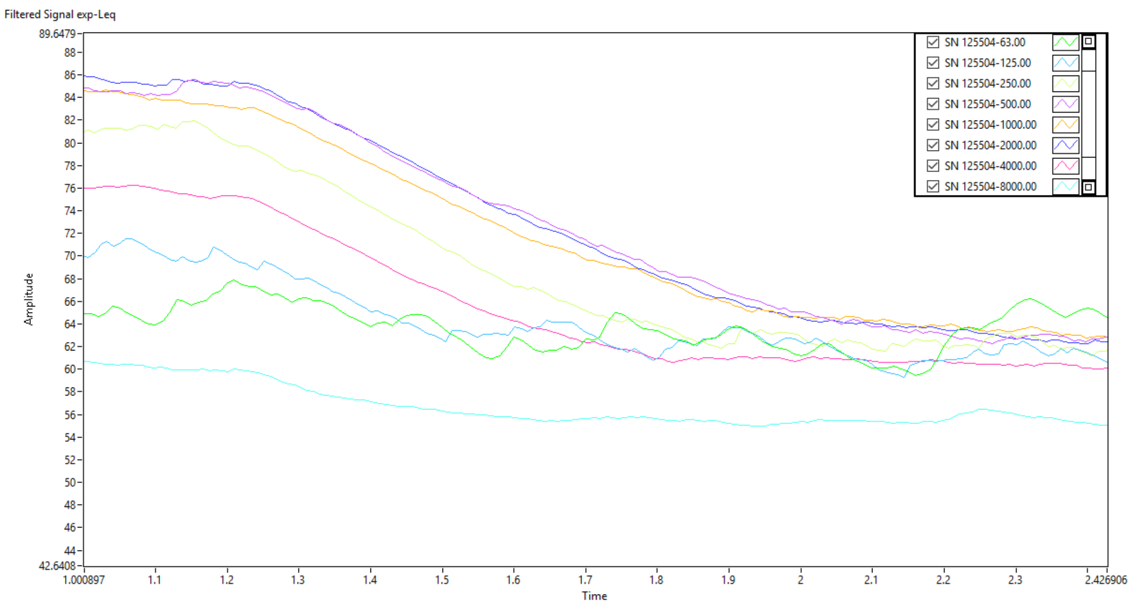

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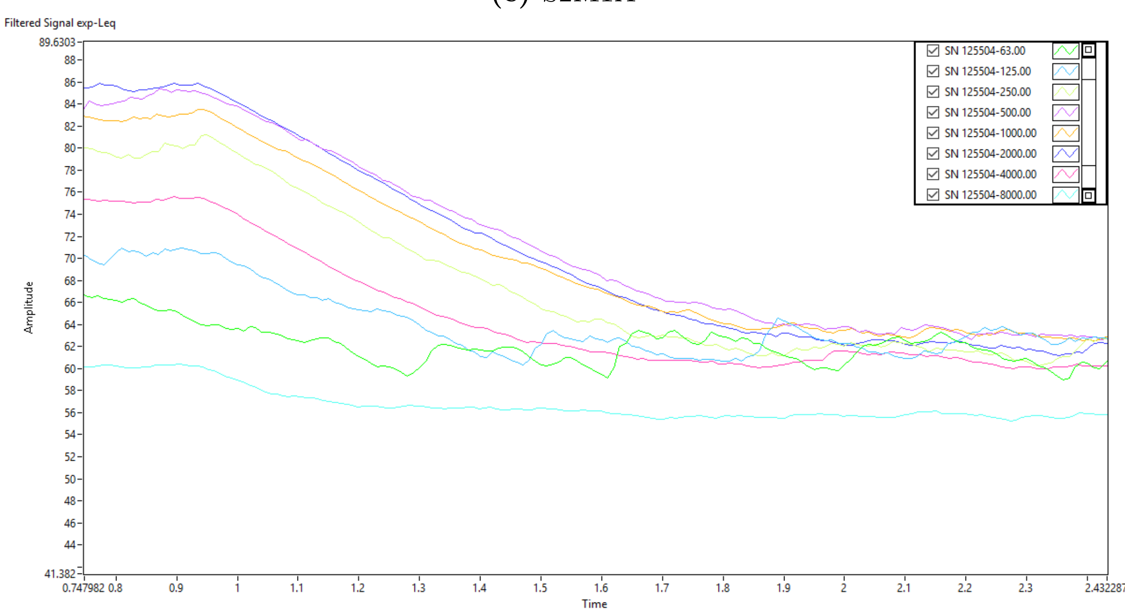

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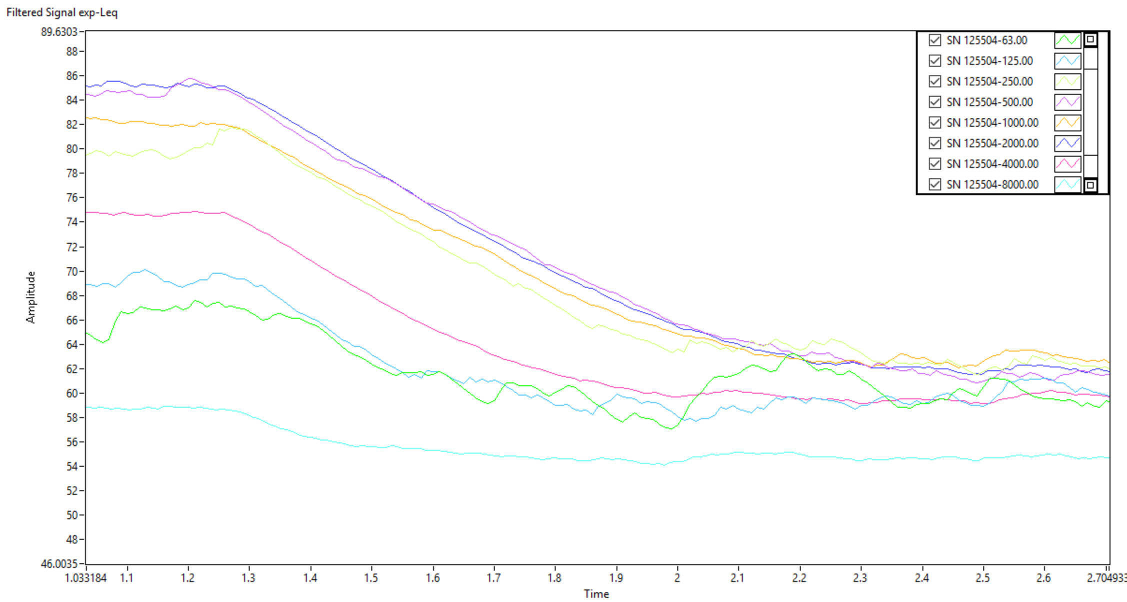

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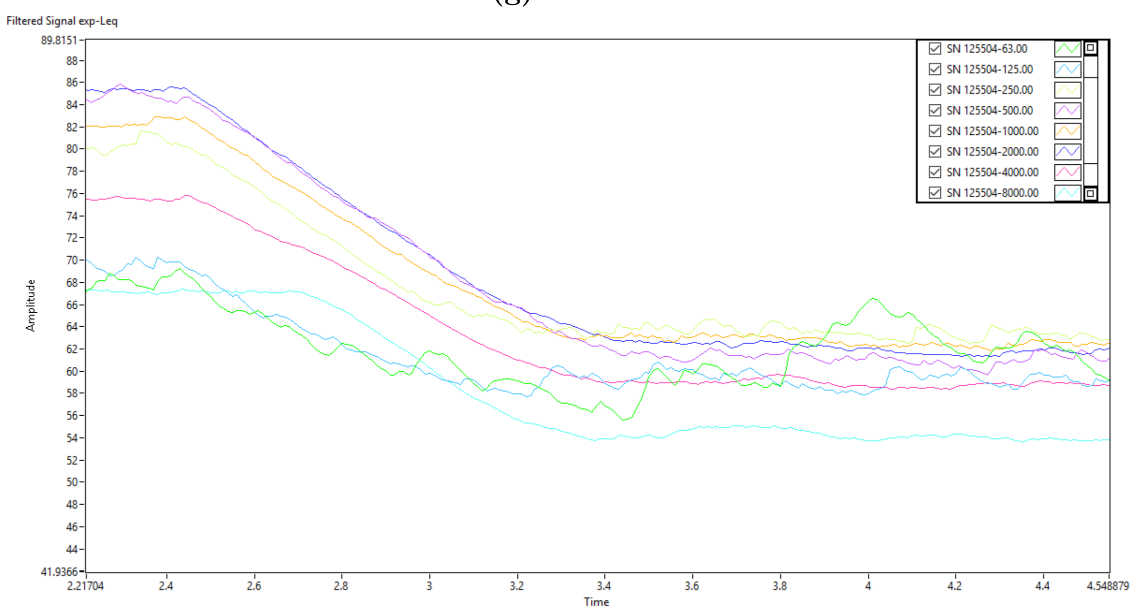

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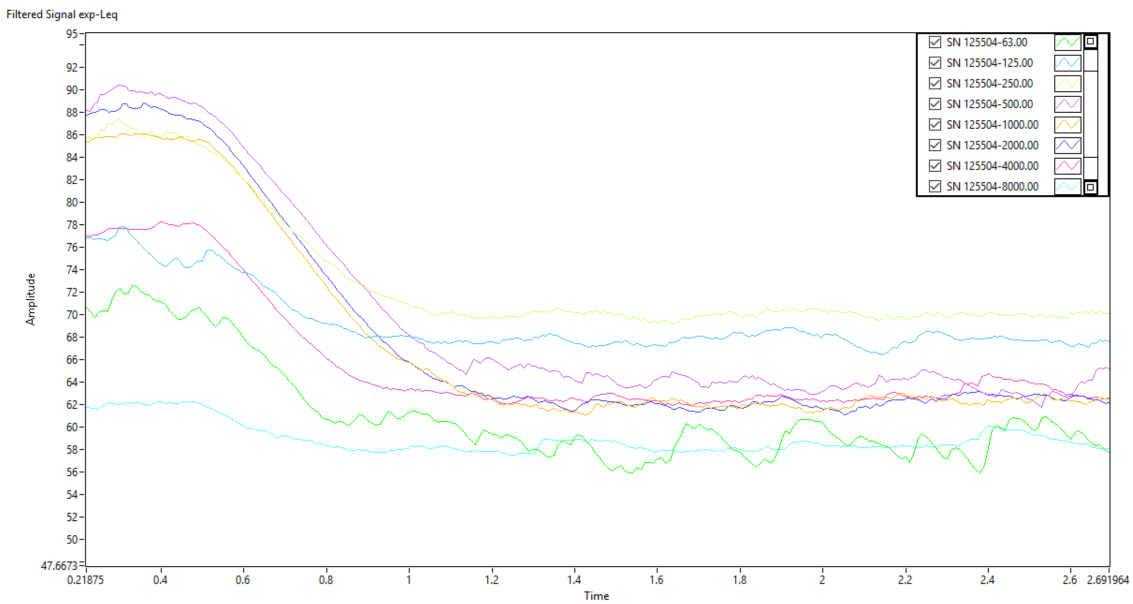
Figure B.1: Broodstock room reverberation time decay curves.



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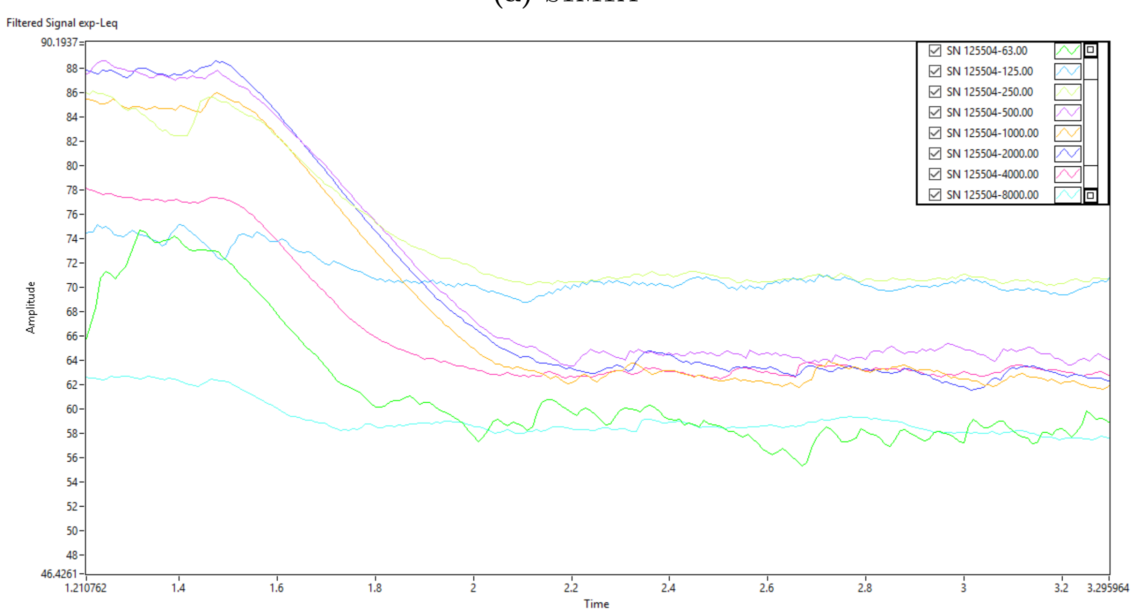

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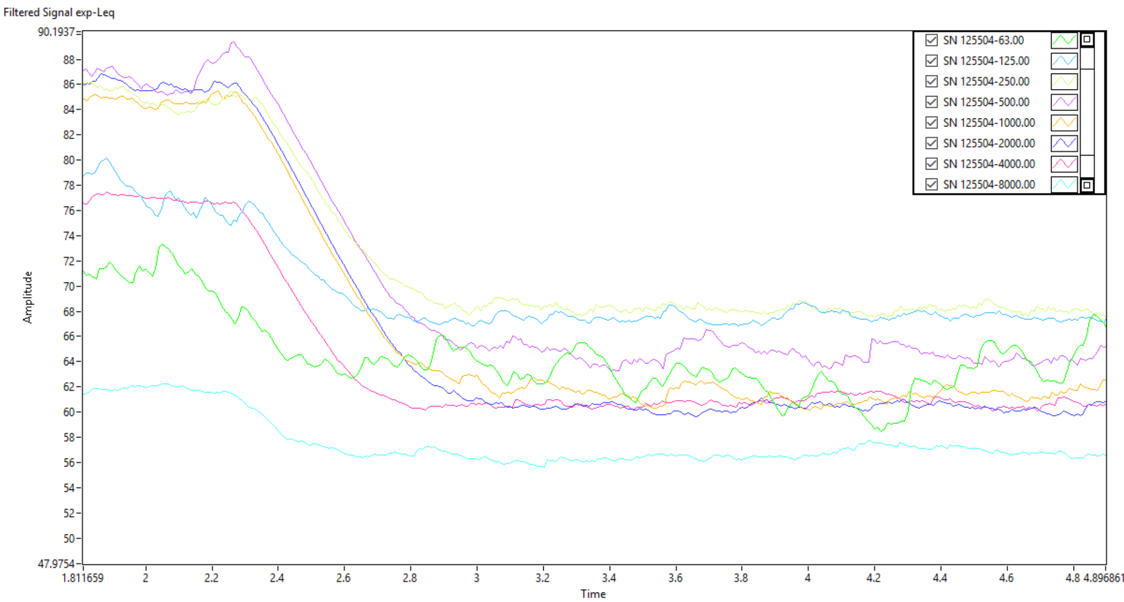

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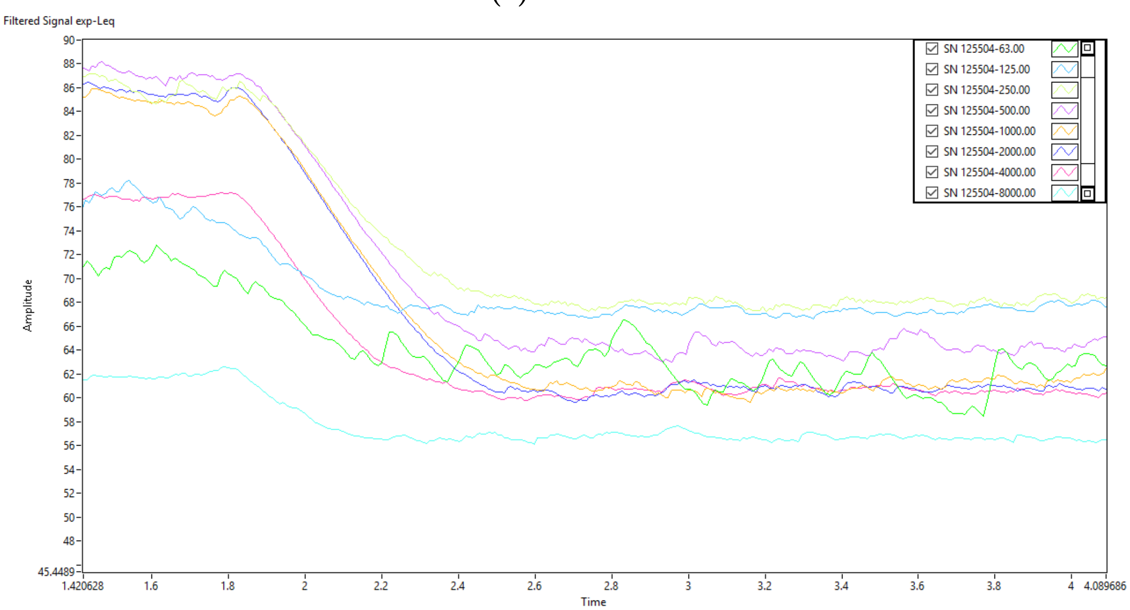

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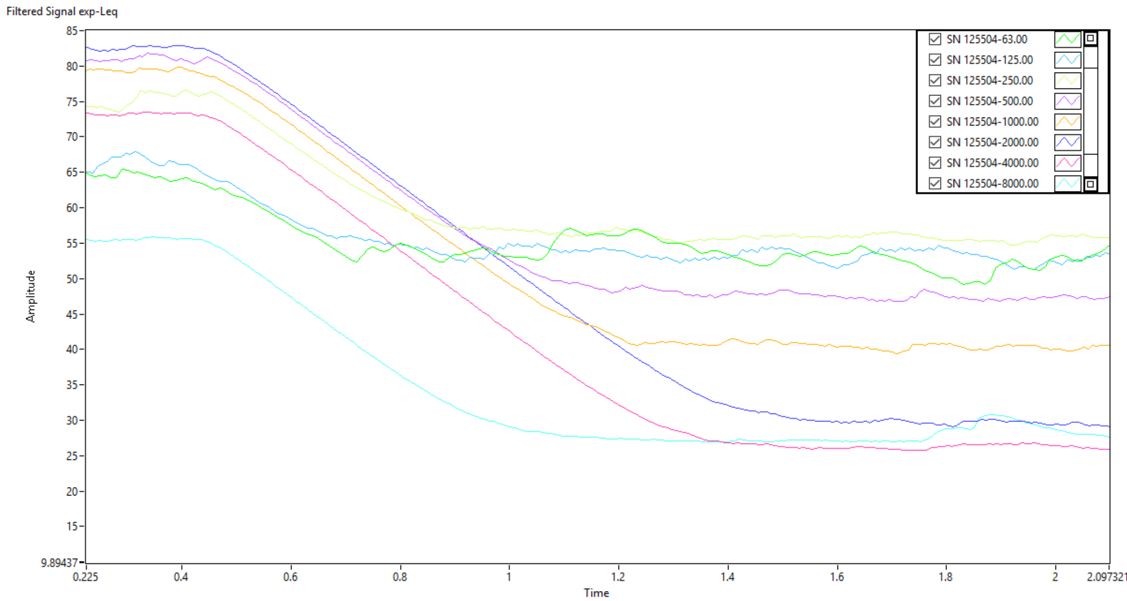
Figure B.2: Hatchery reverberation time decay curves.



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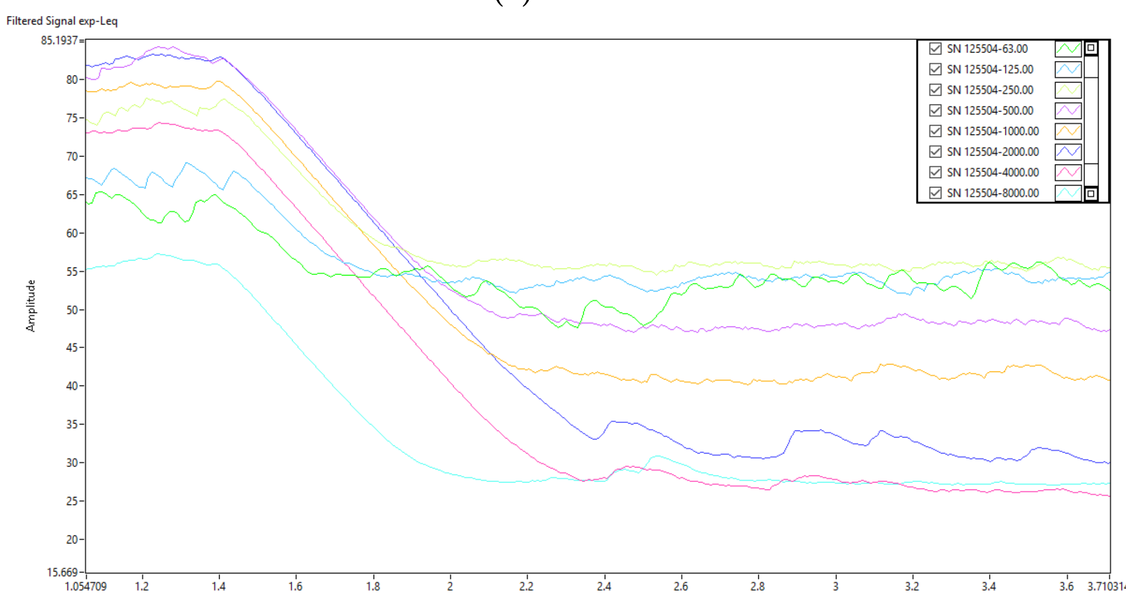

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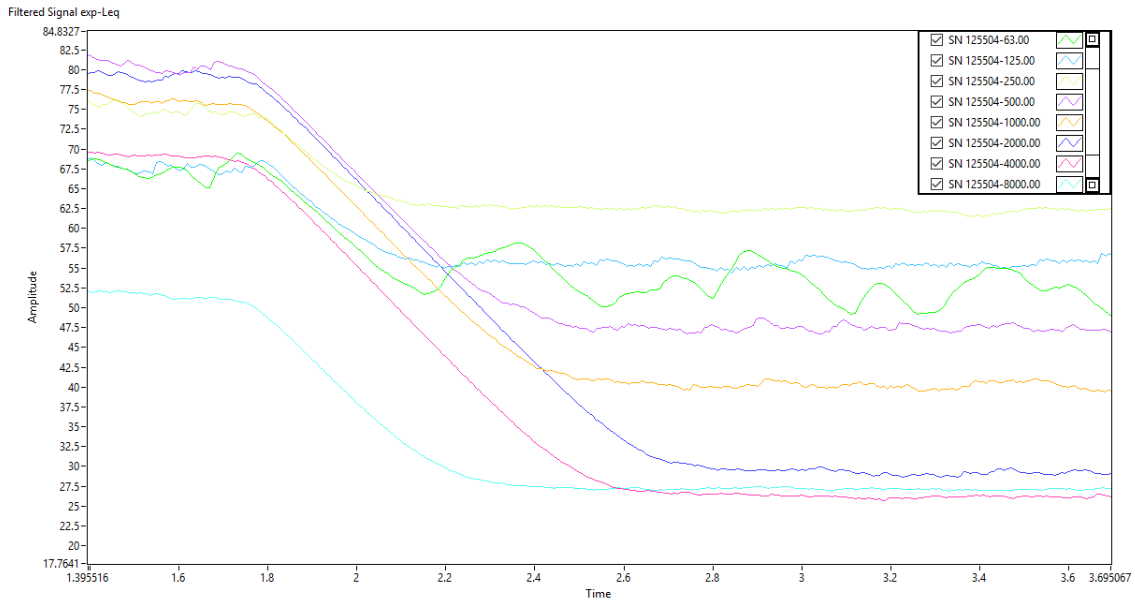
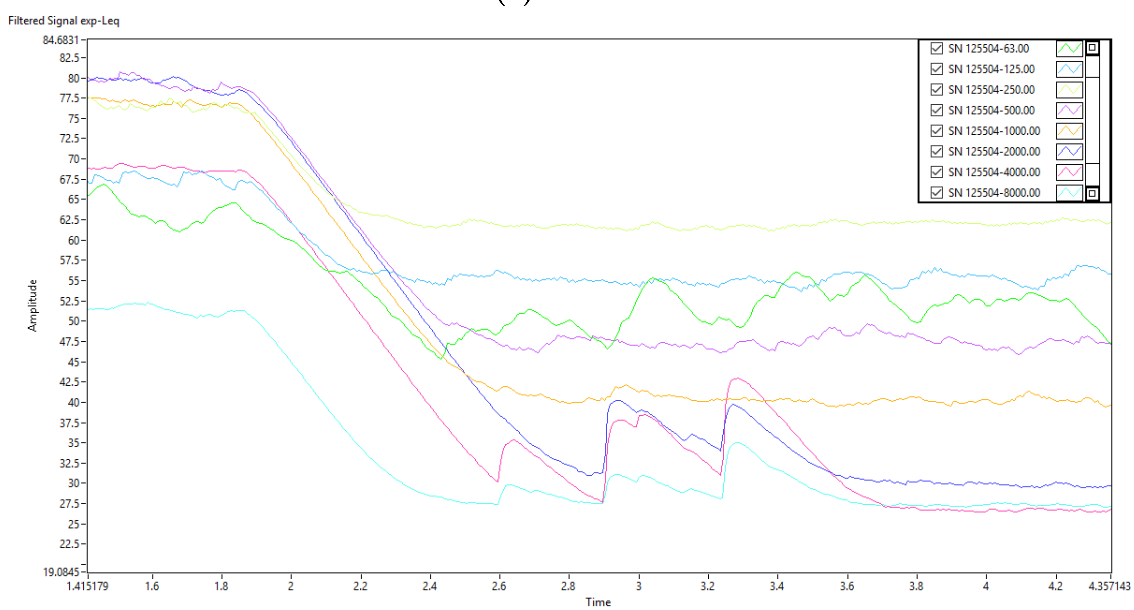
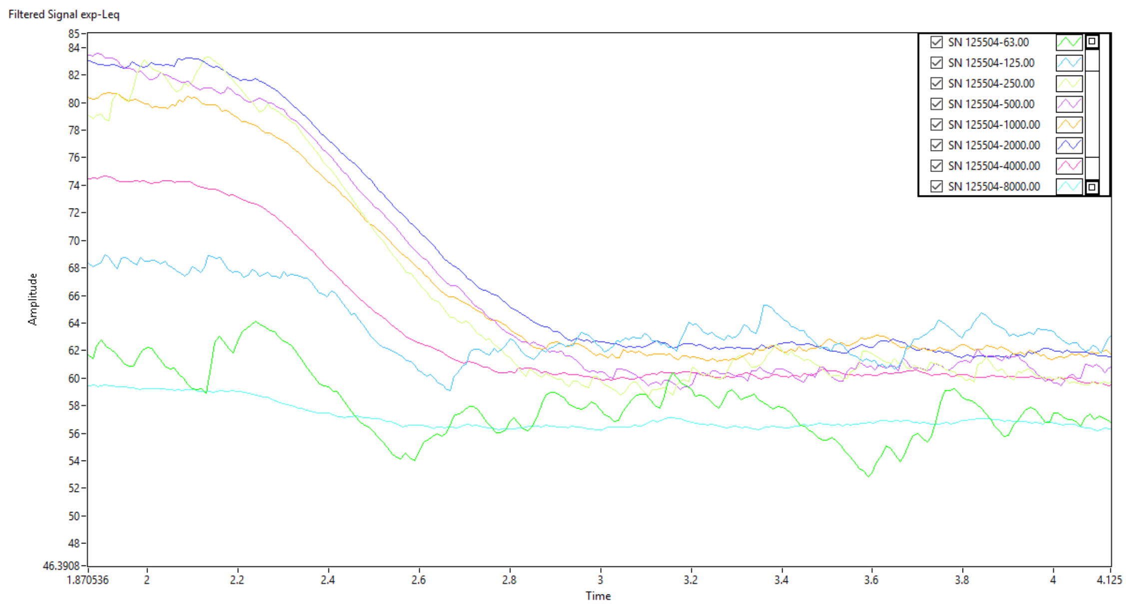


(c) S1M2A

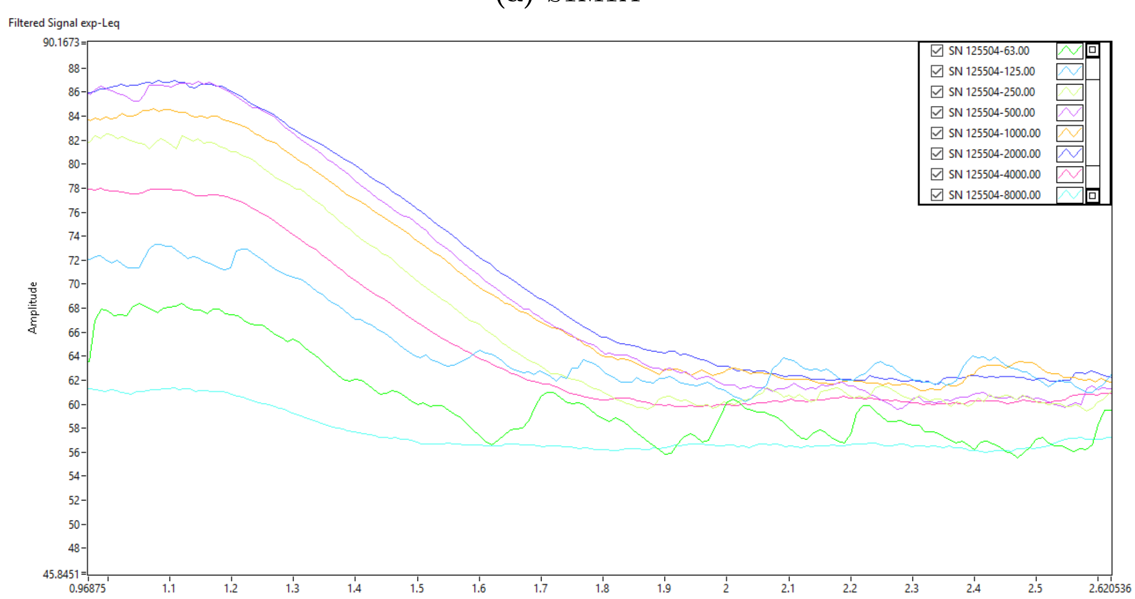


(d) S1M2B

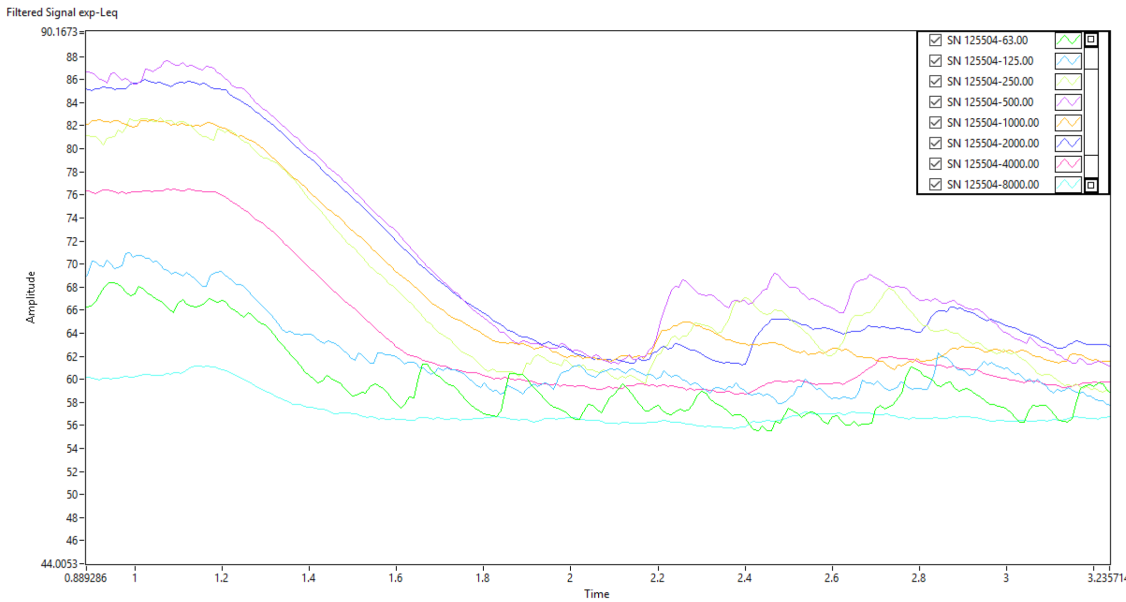
Figure B.3: Office reverberation time decay curves.



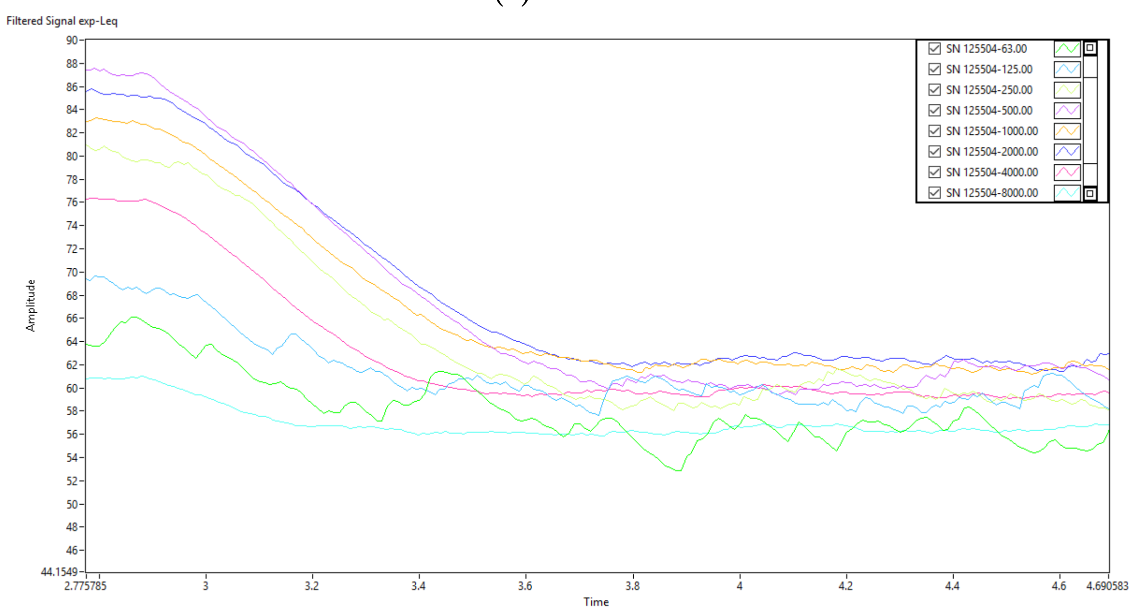
(a) S1M1A



(b) S1M1B

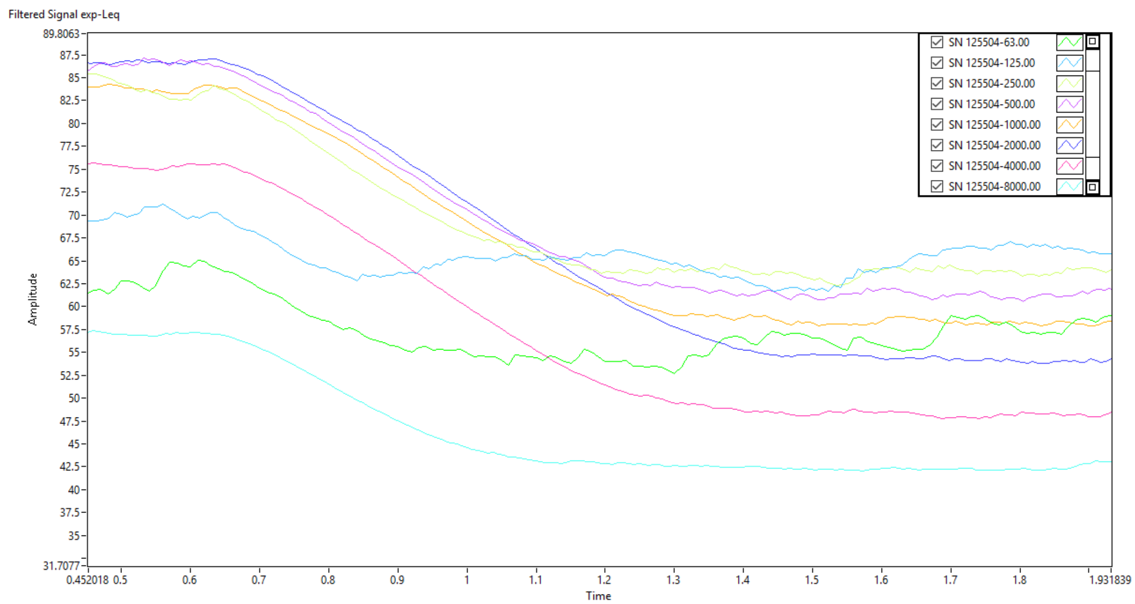


(c) S1M2A

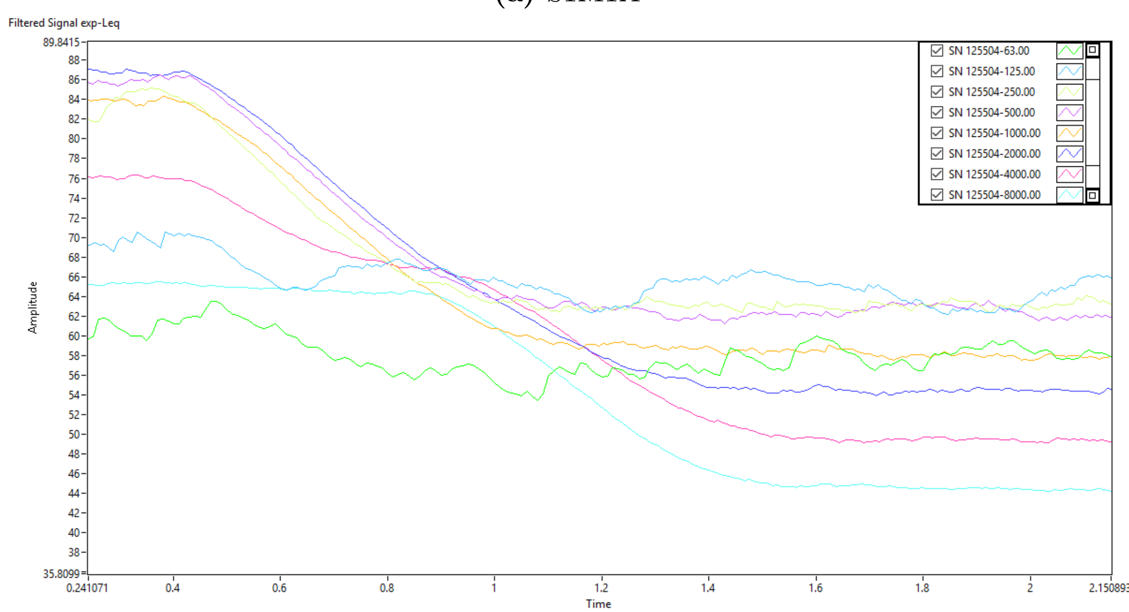


(d) S1M2B

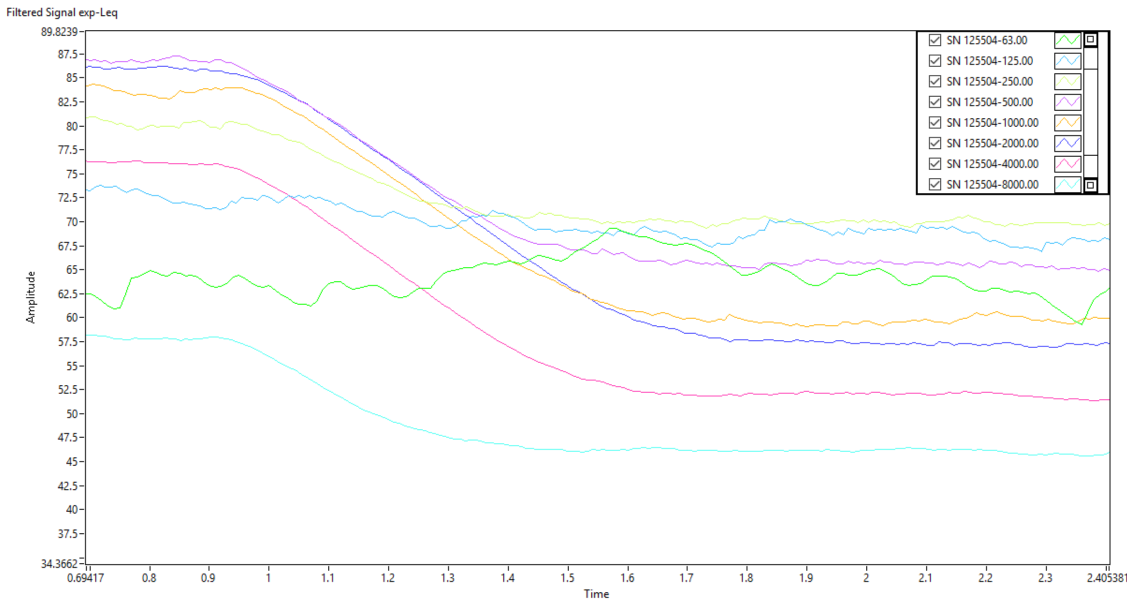
Figure B.4: First Feeding room reverberation time decay curves.



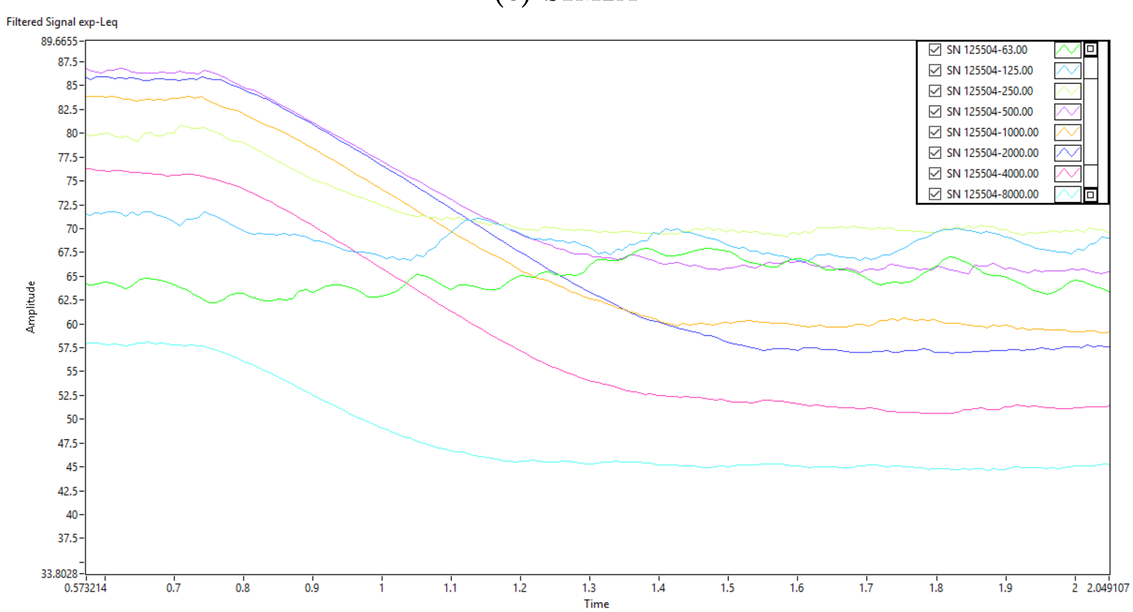
(a) S1M1A



(b) S1M1B

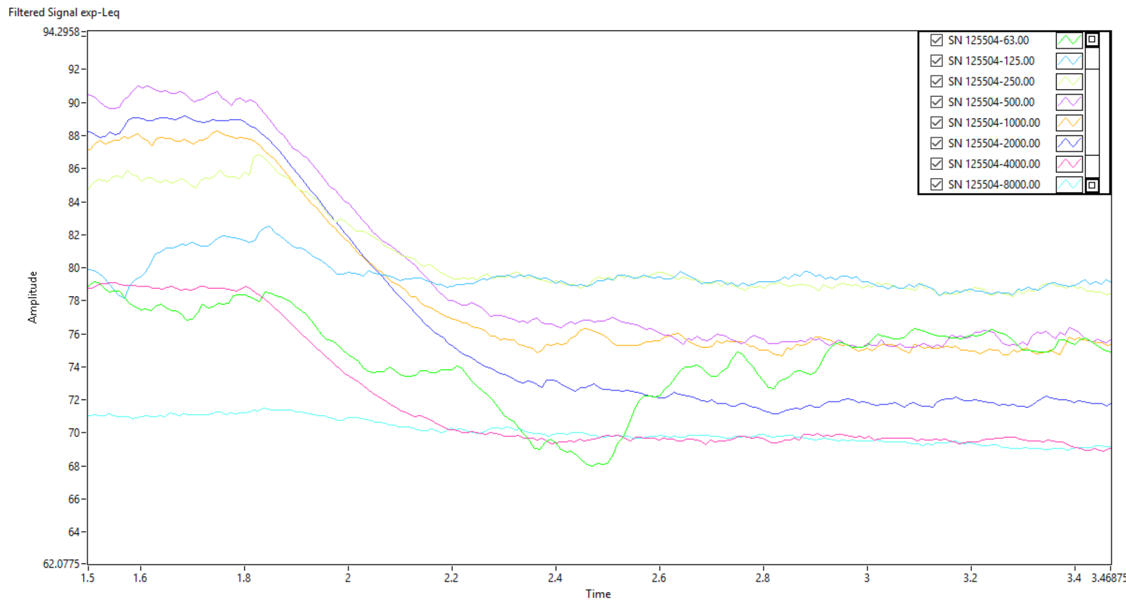


(c) S1M2A

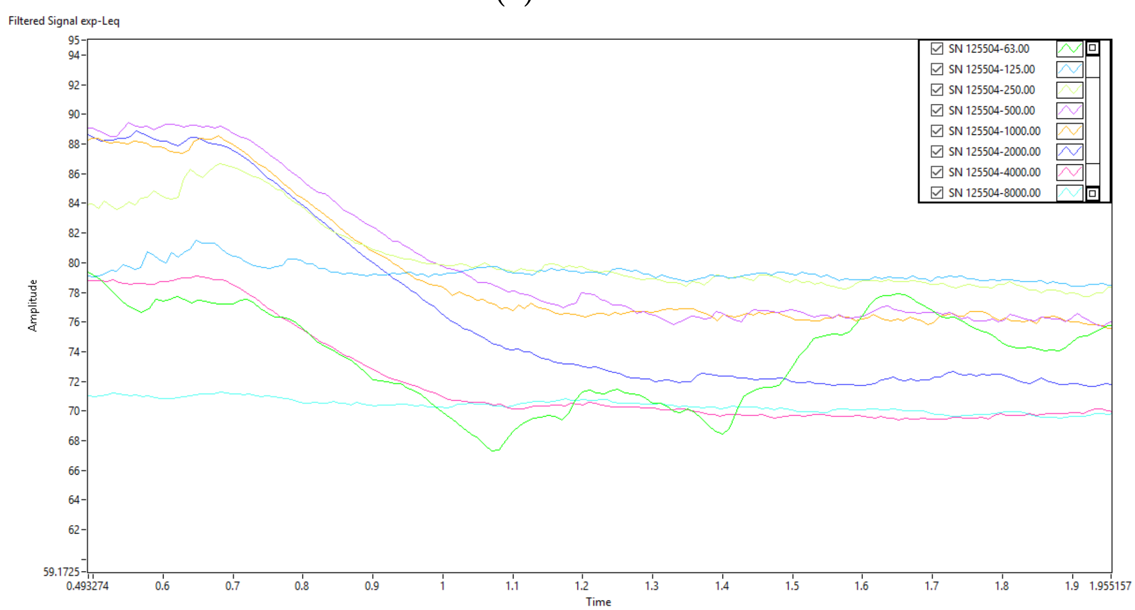


(d) S1M2B

Figure B.5: Prep room B reverberation time decay curves.

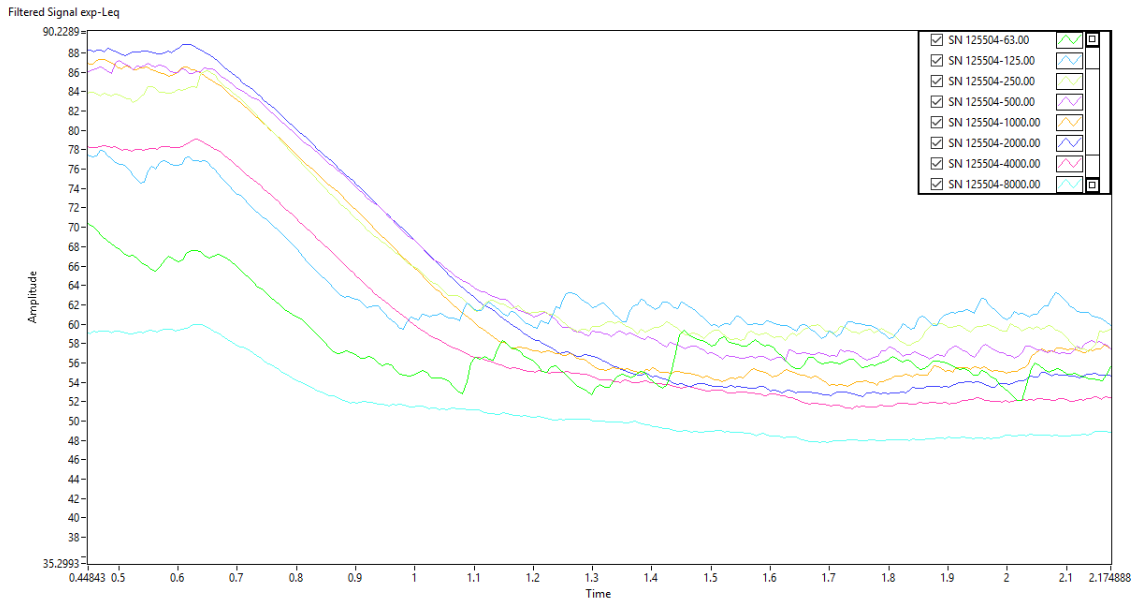


(a) S1M1A

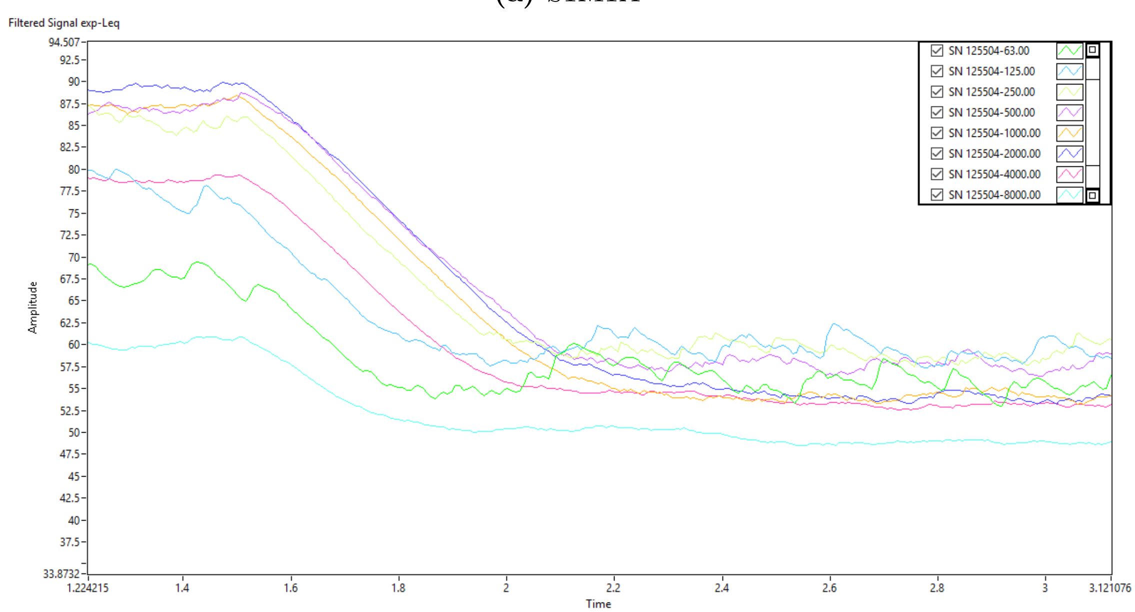


(b) S1M1B

Figure B.6: Filtration room reverberation time decay curves.



(a) S1M1A



(b) S1M1B

Figure B.7: Rotifer room reverberation time decay curves.

Appendix C

Latin Hypercube Designs for Absorption Coefficient Optimization

Table C.1: Latin hypercube design used for the absorption coefficients (α) in the Broodstock room.

Test Case	Walls [-]	Ceiling [-]	Fiberglass [-]	HDPE [-]
1	0.048	0.255	0.350	0.085
2	0.438	0.338	0.372	0.242
3	0.243	0.018	0.385	0.143
4	0.190	0.149	0.054	0.073
5	0.014	0.055	0.284	0.228
6	0.078	0.453	0.222	0.110
7	0.107	0.381	0.185	0.039
8	0.150	0.154	0.253	0.094
9	0.499	0.291	0.206	0.008
10	0.269	0.320	0.139	0.164
11	0.060	0.241	0.148	0.051
12	0.452	0.494	0.078	0.026
13	0.392	0.424	0.099	0.174
14	0.364	0.218	0.179	0.216
15	0.323	0.044	0.279	0.190
16	0.407	0.445	0.101	0.298
17	0.207	0.091	0.029	0.195
18	0.280	0.187	0.005	0.133
19	0.326	0.122	0.328	0.280
20	0.174	0.370	0.305	0.269

Table C.2: Latin hypercube design used for the absorption coefficients (α) in the Hatchery.

Test Case	Walls [-]	Ceiling [-]
1	0.402	0.414
2	0.393	0.306
3	0.142	0.238
4	0.004	0.128
5	0.241	0.338
6	0.072	0.188
7	0.312	0.288
8	0.204	0.444
9	0.115	0.398
10	0.483	0.473
11	0.359	0.478
12	0.464	0.369
13	0.038	0.003
14	0.076	0.032
15	0.348	0.078
16	0.293	0.102
17	0.439	0.072
18	0.185	0.215
19	0.153	0.150
20	0.263	0.259

Table C.3: Latin hypercube design used for the absorption coefficients (α) in the Office.

Test Case	Bricks [-]	Walls [-]	Ceiling [-]
1	0.217	0.162	0.099
2	0.036	0.334	0.301
3	0.076	0.015	0.487
4	0.389	0.384	0.002
5	0.349	0.256	0.465
6	0.352	0.461	0.278
7	0.302	0.109	0.194
8	0.416	0.193	0.052
9	0.069	0.054	0.103
10	0.230	0.489	0.215
11	0.162	0.209	0.259
12	0.261	0.029	0.136
13	0.483	0.368	0.403
14	0.198	0.290	0.445
15	0.278	0.136	0.400
16	0.001	0.414	0.153
17	0.123	0.448	0.344
18	0.454	0.081	0.369
19	0.127	0.324	.034
20	0.450	0.239	0.242

Table C.4: Latin hypercube design used for the absorption coefficients (α) in the First Feeding room.

Test Case	Walls [-]	Ceiling [-]	Fiberglass [-]	HDPE [-]
1	0.193	0.008	0.194	0.133
2	0.121	0.061	0.392	0.072
3	0.138	0.153	0.263	0.026
4	0.179	0.020	0.348	0.176
5	0.008	0.146	0.100	0.090
6	0.186	0.131	0.176	0.194
7	0.117	0.180	0.023	0.182
8	0.011	0.184	0.286	0.047
9	0.169	0.042	0.235	0.084
10	0.034	0.058	0.310	0.034
11	0.028	0.101	0.372	0.100
12	0.142	0.072	0.328	0.159
13	0.068	0.192	0.144	0.125
14	0.075	0.164	0.018	0.015
15	0.090	0.112	0.204	0.169
16	0.106	0.037	0.063	0.001
17	0.090	0.128	0.093	0.061
18	0.158	0.017	0.131	0.116
19	0.046	0.094	0.049	0.142
20	0.057	0.082	0.246	0.059

Table C.5: Latin hypercube design used for the absorption coefficients (α) in Prep room B.

Test Case	Walls [-]	Ceiling [-]
1	0.308	0.344
2	0.157	0.199
3	0.036	0.157
4	0.062	0.446
5	0.428	0.468
6	0.415	0.369
7	0.464	0.411
8	0.495	0.211
9	0.231	0.230
10	0.211	0.303
11	0.091	0.030
12	0.332	0.051
13	0.147	0.295
14	0.375	0.127
15	0.285	0.399
16	0.109	0.094
17	0.010	0.025
18	0.252	0.108
19	0.384	0.252
20	0.187	0.486

Table C.6: Latin hypercube design used for the absorption coefficients (α) in the Filtration room.

Test Case	Walls [-]	Ceiling [-]
1	0.210	0.052
2	0.456	0.198
3	0.049	0.469
4	0.004	0.364
5	0.315	0.161
6	0.365	0.478
7	0.067	0.220
8	0.386	0.301
9	0.443	0.289
10	0.416	0.130
11	0.116	0.087
12	0.159	0.267
13	0.083	0.014
14	0.275	0.232
15	0.176	0.327
16	0.141	0.403
17	0.495	0.047
18	0.252	0.447
19	0.243	0.103
20	0.336	0.384

Table C.7: Latin hypercube design for the absorption coefficients (α) in the Rotifer room.

Test Case	Walls [-]	Ceiling [-]	Fiberglass [-]
1	0.065	0.227	0.376
2	0.267	0.310	0.335
3	0.401	0.132	0.471
4	0.388	0.406	0.054
5	0.368	0.490	0.034
6	0.323	0.369	0.136
7	0.435	0.099	0.219
8	0.346	0.388	0.274
9	0.098	0.059	0.444
10	0.485	0.218	0.191
11	0.018	0.262	0.159
12	0.291	0.294	0.475
13	0.107	0.118	0.095
14	0.129	0.334	0.281
15	0.166	0.453	0.403
16	0.026	0.003	0.313
17	0.201	0.045	0.121
18	0.470	0.440	0.230
19	0.181	0.178	0.013
20	0.235	0.169	0.372