# The Reintroduction of Natural Ventilation to a 19$^{th}$ Century Opera House, Utilising Calibrated Computer Simulation and User Operation

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## ABSTRACT

The Royal Wanganui Opera House (RWOH), in Whanganui, New Zealand, was constructed in 1899, and now seats 830 people. This building was designed with a natural ventilation system; however, this system is no longer in operation and the RWOH has received regular complaints from patrons regarding indoor thermal comfort. Various options for mechanical systems to improve indoor comfort during summer performances have been considered, but have been deemed too costly. The RWOH is listed with Heritage New Zealand as a Category 1 heritage building. Without an effective ventilation scheme, the selection of the RWOH as a performance venue during peak summer months is threatened. The addition of a mechanical ventilation system will not only be costly, but also encounter issues complying with the building's heritage listing. The potential benefits of a natural ventilation scheme for the RWOH regarding initial cost, thermal comfort, and on-going maintenance costs for the local Council are key drivers of this investigation. An additional benefit is the functional heritage value: restoring the building technology to its original design.

A calibrated Computational Fluid Dynamics (CFD) software analysis of the RWOH has been completed. Temperature and humidity monitoring devices were placed throughout the auditorium, stage, and roof space to gain data to calibrate CFD modelling of the space. Because temperature monitoring devices are reliable, cheap and readily accessible, temperature, rather than airflow, was selected as the calibration medium at multiple points in the auditorium for the ventilation simulations. The CFD analysis investigated the building's potential for the reintroduction of a natural ventilation scheme in several incremental stages. Incremental changes to the operation of openings in the building have been completed: it saw reintroduction of natural ventilation airflows as tested through the CFD modelling. Staff at the RWOH were given an operation guide for the sold out performance of the New Zealand Opera School on Saturday the 21$^{st}$ January 2017, a performance that in previous years has sparked multiple complaints from the audience regarding comfort issues. No comfort complaints were received after this year's Opera School Performance. While the weather during this key performance was not as warm or detrimental to the indoor thermal comfort as it has been in previous years, the owners and operators of the RWOH are now aware of the benefits the changes to the operation of the building's ventilation openings has already achieved. The owners of the RWOH are interested in undertaking further stages of renovations in order to continue to improve the ventilation of the building for the future. The research team is currently devising a guide for the application of successful natural ventilation schemes to similar buildings throughout New Zealand.

## KEYWORDS

Natural ventilation, passive, CFD, simulation

## 1 INTRODUCTION

Of the many ways in which the internal environment can be improved in our buildings, the issue of providing fresh air to people in crowded situations such as auditoria and school classrooms is particularly challenging. Of these situations the large theatre is an extreme example. This paper explores the application of CFD analysis to the understanding of the natural ventilation designed into a 100+ year old theatre; calibration of the CFD predictions against measured data; and observation of the efficacy of design and operation interventions suggested by the CFD analysis.

### 1.1 An Overview of the Royal Wanganui Opera House Project

The Royal Wanganui Opera House (RWOH) is an 830 seat theatre in Whanganui, New Zealand. Due to its recent comfort complaints, seismic renovations, and a history of natural ventilation design, the RWOH became the major case study for this research. The owners of the RWOH, the Whanganui District Council, wish to find a cost effective solution to ensure the building’s use as a performance space can continue.

The original design of the RWOH was explored, and changes through its life span that have affected the ventilation were identified. The basic geometry of the building was 3D computer modelled in Revit. Temperature and humidity sensors were placed throughout the auditorium itself to collect measured data regarding the building’s existing operation. The measurements were taken at 5 minute intervals over a two week period during winter. The goal was to obtain sufficient data to build quickly a trustable analytical model, which would enable the modification of the building prior to an early summer performance that has had a full house in past seasons and has engendered significant overheating complaints.

The geometry was imported into Autodesk Simulation CFD (Autodesk Inc., 2015), and selected situations (weather conditions, occupancy numbers, known openings, use of equipment) of the building were simulated. The CFD model was calibrated against a series of observations of the performance of the existing building. CFD modelling to test the likely success of new or restored interventions to the ventilation scheme was then undertaken. The input data was taken from weather data measured in the area at the same time as the measurements. The results of the CFD models were compared with the measured temperature and humidity data from inside the auditoria, entrance area, roof space, and back of stage. Once the model’s geometry, materiality, solar exposure, and internal heat loads produced results aligned with the measured temperature data, these modelling conditions were confirmed and the design option modelling process could begin.

Once calibrated, the model was used in a fully occupied state to analyse performance in summer weather conditions. The goal was to assess key problem areas for overheating in the occupied space. This knowledge acquired from the analysis of the existing building helped identify the proposed ventilation alterations. The designs were then discussed with the building owners for construction feasibility, and the underlying geometry model was altered to reflect the proposed designs. The CFD analysis helped form design and operation recommendations focused on potential comfort hours in summer. From these recommendations, the project to mitigate the RWOH’s overheating issues in summer months was split into two stages. Stage one necessitated immediate operational changes for an imminent heavily occupied performance. Stage two is currently underway, and involves constructional changes to the building.

### 1.2 History of Naturally Ventilated Auditoria Design

Bringing natural ventilation back into auditoria buildings restores the original operational approach for historic theatres. “Destruction or refurbishment of 19$^{th}$ Century theatres has meant that there are few remaining vestiges of the old natural ventilation systems to be found”

(Kenton 2004). The design of naturally ventilated auditoria has had a resurgence due to the global energy crisis (Kenton, 2004). Not only does natural ventilation hold biophilic significance and comfort improvements, but it also has the potential to save operational energy (Kellert, Heerwagen, & Mador, 2008).

According to the Chartered Institution of Building Services Engineers (CIBSE) Ventilation Guide B, in 2005 little data existed regarding natural ventilation in buildings where floor-to-ceiling height exceeded 3.5m. By studying history and modelling a complex and extreme case, the intention is to get closer to normalising this type of space. While natural ventilation is not without design challenges, the benefits include a reduction in headaches, and often more highly oxygenated air than would be provided by mechanical means (Kellert, Heerwagen, & Mador, 2008). The issue is how to achieve these qualitative improvements even in the crowded and difficult circumstances of an auditorium, and whether the answer lies in the historical methods of natural ventilation.

### 1.3 Use of Computational Fluid Dynamics (CFD) in Natural Ventilation Design

As a design tool, CFD is unique as it can predict the air motion at all points in the flow. CFD modelling can be used to predict temperature and velocity fields inside buildings for steady-state problems (Allard, 1998). Due to the intensive nature of the computations, CFD is normally only used to generate ‘snapshots’ of how the design would work at a given point in time (CIBSE, 2005). Accordingly, this software can be used to test extreme or representative conditions at a single point in time. This is different from thermal analysis programs, which today generally calculate an energy balance for each hour of a typical year. This is a key limitation of CFD, as the modelling does not take into account what is happening in the space before and after the analysis, making the specification of boundary conditions to define the existing space extremely important.

With the addition of thermal equations, CFD can predict the effects of buoyancy and the temperature field, addressing questions of stratification and local air movement (CIBSE, 2007). This is particularly important in auditoria such as RWOH, as inlet and outlet levels as well as the height of an auditorium, affect the stratification levels of air. Warm stale air collects below the ceiling; CFD can be used to test whether this air will remain above the occupied zone (Short & Cook, 2005). Since indoor conditions of naturally ventilated spaces are difficult to predict using alternative building simulation tools, the use of CFD simulation becomes necessary (Hajdukiewicz, Geron & Keane, 2013).

## 2 ABOUT THE CASE STUDY: THE ROYAL WANGANUI OPERA HOUSE

The Royal Wanganui Opera House (RWOH) was designed by Wellington architect, George Stevenson, in 1899. The building has a history of natural ventilation design, but the many alterations since the building’s construction have seen this system become obstructed. Having recently completed seismic strengthening work, the Whanganui District Council became interested in making the internal environment more comfortable for the audience during summer performances. Designed to ventilate without mechanical assistance, the RWOH in its existent state with an 830 person occupancy received numerous complaints regarding the internal air quality during performances during previous summer months.

The building has a large dome above the main seating area with a grille vent into the ceiling space, Figure 2. From the ceiling space, original plans show two penthouse louvres located above the stage space and seating area, seen in Figure 3. The large penthouse louvre over the seating area has been replaced with a curved ridge vent with a smaller aperture, Figure 4. The penthouse louvre over the stage has also been replaced with a ridge vent, however the opening was boarded up (seen as image 3 of Figure 9). Within the auditorium, multiple external openings are situated at the perimeter of the high level seating space, Figure 2. These openings appear to be the main exhaust air location for the higher level seating. Due to light and noise pollution, these openings are no longer opened, but are shut tight during performances. Despite comfort complaints, no mechanical system has been added. An upgrade to the system is urgently required.

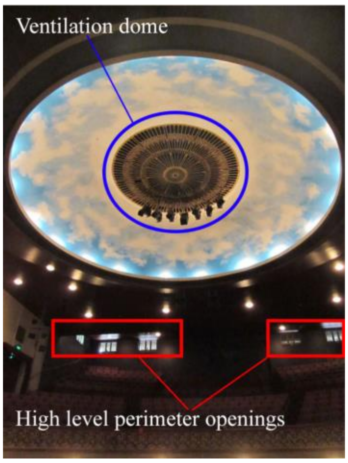




Figure 1: The Royal Wanganui Opera House (Wanganui Opera Week, 2016).

Figure 2: The Dome above the Seating Area, and External Perimeter Openings (Author’s Image, 2016).

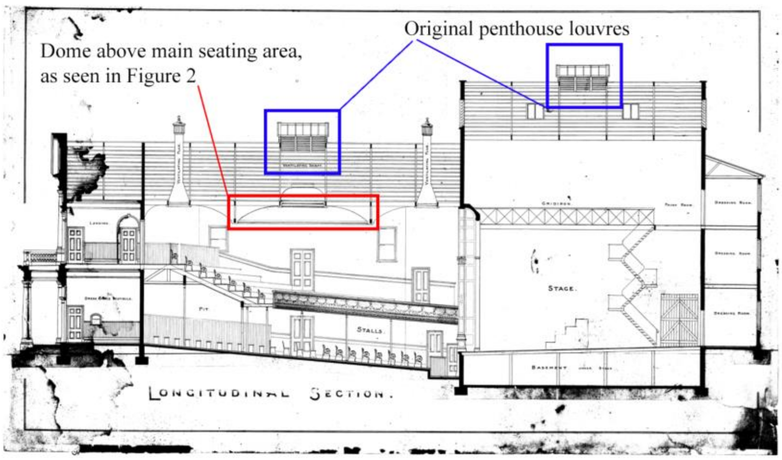



Figure 3: Longitudinal Section of the Wanganui Opera House, completed by architect George Stevenson, 1899.

Figure 4: Existing Ridge Vent Replacement of Penthouse Louvres (Author’s Image, 2016).

## 3 3D COMPUTER GEOMETRY MODELLING

A combination of original plans, updated drawings from the recent seismic renovations, photographs, and measurements taken on site contributed to the 3D modelling of the RWOH in Autodesk Revit Software. In order to import a 3D model into Autodesk CFD (the air flow assessment software) the 3D model needs to be as simple as possible. A basic Revit model has been completed of the space, maintaining volume, wall area and the shell geometry. Due to the hierarchy of importance of elements and low complexity level required for a CFD model, ensuring the external shell and volume within the occupied space is as closely aligned

with reality as possible was the main priority. Elements such as columns within the seating area, individual seating and balustrades were not modelled due to their likely minimal effect on air flow. The operable area of openings has been modelled, and each external window and door has been modelled as a slot, even when closed, to account for air seepage.
Detail has been incrementally added to the model to more closely to align the simulated result with the measured data. The dome ceiling shape needed to be made more complex in order to reflect the pattern of air within the space, see Figure 5.

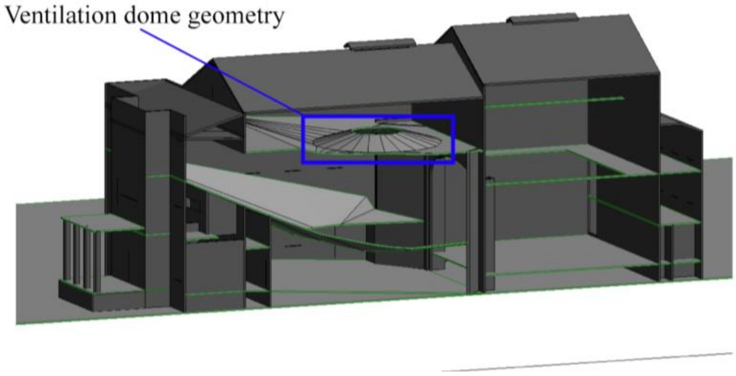



Figure 5: Longitudinal Section through the 3D Model of RWOH, showing the detail required for the dome ceiling in order to calibrate the CFD analysis.

## 4 COLLECTION OF TEMPERATURE DATA

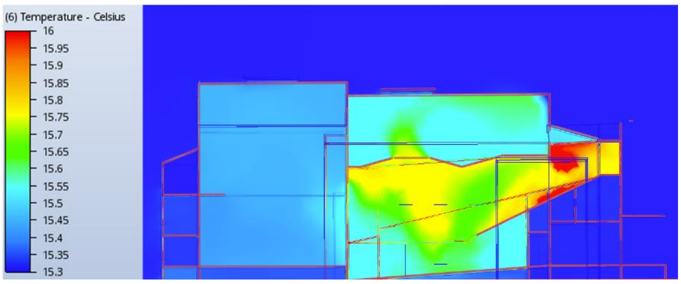
To calibrate the CFD simulation of the existing situation, thirteen calibrated Testo-175-H2 temperature and humidity recording devices were placed throughout the RWOH for a period of two weeks, set to record at 5-minute intervals. The Testo devices were themselves calibrated against an aspirated hygrometer temperature standard prior.

During the two-week period, several performances occurred including a local school production. While the Testo devices were largely left to run unattended, the day performance of the school production was attended in order to make operational alterations to the ventilation of the space during the interval. Due to the one-off nature of the CFD calculation, the calibration exercise was deliberately planned to test the model under as wide a range of operational and occupancy conditions as was feasible in the time available. The smoke exhaust bypass ‘butterfly’ dampers above the dome in the main seating area (image 2 in Figure 9), one of the vents above the high level seating (image 7 in Figure 9), the sliding shutters in the roof above the stage area (image 3 in Figure 9), and the roof access door above the stage area (image 6 in Figure 9) were opened for the second half of the performance.

Recordings from these performances, as well as when the building was empty, and real time external data from the Whanganui Weather Station provide the calibration data (NIWA, 2016). The recorded data of the temperature measurements taken during the two performances, in different weather conditions, show stratification in air temperature. The major test for the CFD simulations was to ensure it could re-create this stratification of air temperatures.

## 5 CFD CALIBRATION

Calibration of the CFD modelling for the RWOH consisted of two stages. First, the model of the existing building was calibrated for the building’s simplest situation: an unoccupied space during temperate weather conditions. Following a series of simulated iterations, incrementally altering the boundary conditions, turbulence equations, solar radiation inputs, wind speed ratios, existing surface temperatures, assumed dimensions, and modelled materiality, the CFD outputs aligned with the measured data and fitted within the specified calibration tolerances and the limitations of the measuring devices.



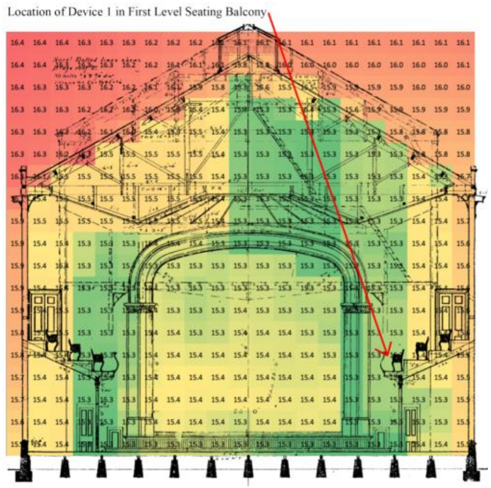




Figure 6. The Calibrated Occupied Model of 10.45am on the 20th September 2016, showing stratification of air and aligned results with measured data points.

Figure 7. A Cross Section of Exported Data from CFD, overlaid with architecture and device 1 location.

The second stage of the CFD modelling involved calibrating two models of the RWOH during an occupied time, when the number of occupants and state of the openings were known. One of the models depicted the space occupied as it is in usual operation with the majority of the openings closed; the second occupied model simulated the space when several high level openings had been opened. These models used the materiality, turbulence equations, solar radiation process, and assumed dimensions, that were confirmed in the stage one calibration. Following a series of simulated iterations, to determine the most effective way of modelling human heat gains within the space to decipher their influence on air temperature, the outputs from both models became aligned with the measured data and fitted within the specified calibration tolerances and the limitations of the measuring devices. The CFD output of a calibrated model of the occupied space can be seen in Figure 6, and Figure 7 shows the exported CFD data overlaid with the architectural drawings to identify the temperature measuring device location for numerical analysis.

## 5.1 Calibration Conclusions

While this study is based on CFD analysis, ultimately the measure of success for subsequent design alterations is the comfort of people within the RWOH. Accordingly, calibrating the CFD modelling by using temperature readings from within this space relates directly to the purpose of the CFD modelling process, and allows calibration utilising a measure that is more feasible to assess accurately across the full height of the auditorium than air movement. The value of calibrated CFD models is their potential for future application, examining the feasibility of reintroducing natural ventilation to modern buildings. This calibration process provided a Quality Assured level of trust in the design iterations that followed. Because the temperature recordings and subsequent calibration exercise was undertaken during spring rather than summer, when comfort issues occur, there is a degree of uncertainty as to whether the CFD modelling will reflect the summer scenario as accurately.

A further outcome of this process was the demonstration that the RWOH's original natural ventilation system with penthouse louvres might have been successful. Successful naturally ventilated spaces not only have the ability to provide healthy and comfortable indoor conditions, but also have the potential to reduce energy consumption. The demonstration of the success of the RWOH system adds strong support to the case that there is historical as well as functional value in the reinstatement of the system. It also suggests that the same process that has been applied to the RWOH could be replicated for many other large-scale historical buildings, which have most likely been designed to provide fresh air in a similar manner without fans or equipment. There is an added value of the calibration process for large-scale CFD models: demonstration of a consistency between prediction and reality. It suggests that CFD may reliably be used to study the feasibility of natural ventilation for modern buildings that house large crowds.

## 6 MODELLING PROPOSED DESIGN CHANGES

The CFD analysis of the summer performance identified several key areas of overheating concern. Potential changes to the RWOH were considered including: operational changes to air inlets, and air outlets; constructional changes to inlets, and outlets; and major alterations to the building. The first alterations tested were operational. These included reopening the ridge vent above the stage space (image 3 in Figure 9), opening the butterfly dampers above the dome (image 2 in Figure 9), and operating the perimeter windows that had been prohibited (image 4 in Figure 9). Allowing perimeter doors to be open during performances greatly improved the inlet air supply, but the operational issues of such a change restricted its uptake. Given the success of this last operational option, a construction change that was considered was operable louvres in these doors.

The major occupied area of concern noted in the CFD modelling, and confirmed by anecdotal evidence, was the high level seating at the back of the auditorium, shown in Figure 8. The shape of the ceiling rising above the high level seating creates a warm air trap. In the original design of the building, high level windows on the three perimeter walls surrounding this area were operable. Since the design of the building in 1899, the adjacent road has become significantly busier with motor vehicles. These windows are no longer opened during performances due to noise, as well as the light leak issues that will have existed from the outset. The constructional change agreed with the building owners was the addition of an airflow route from this high level seating space into the ceiling, by the way of a pelmet slot.

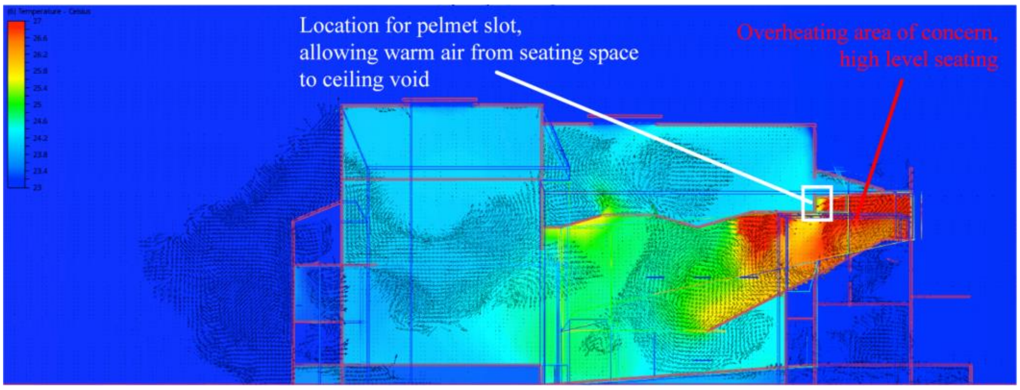



Figure 8. CFD Results from the Fully Occupied Summer Scenario, exposing the key problem area and potential solution.

Major constructional changes tested with CFD included removing the ridge vents (Figure 4), and reintroducing the original penthouse louvres above the stage and dome ceilings, as seen in the original section of Figure 3. The free area of these vents was far greater than their ridge vent replacements, and the height of the penthouse structures likely created a chimney effect. Restoration of the penthouse outlets would be a historical, as well as functional, feature.

## 7 STAGE ONE CHANGES FOR THE RWOH (OPERATIONAL)

Given the restricted timeframe between the assessment of the building and an important performance, ventilation alterations were completed in two stages. The first stage involved ensuring the building was operated as successfully as possible during the New Zealand Opera School's performance in January 2017. A key member of the audience left the show part way through in a previous year, due to the heat and consequent fear of fainting. A repeat of this situation would likely see the building's use in future years becoming greatly reduced. Previously boarded up windows and the stage side ridge vent were rectified before the upcoming performance, but more intrusive construction changes were waitlisted for stage two. An operational user guide was created for this specific performance, Figure 9. This user guide was intended to guide the building management to operate the existing openings in a manner that allowed maximum airflow through the occupied spaces of the auditorium. Due to the importance of thermal comfort, previous restrictions due to traffic noise and light leaks were softened for this performance.

The weather in Whanganui during the Opera School's performance was cooler than previous years, a beneficial aspect for the ventilation. Feedback from the operational team was overwhelmingly positive; members of the audience reported no comfort complaints; temperatures in the space did not exceed 20°C.

## 8 STAGE TWO CHANGES FOR THE RWOH (CONSTRUCTION)

Further work is being completed on the RWOH to safeguard the auditorium in future years, should the weather during summer performances not be as favourable as the night of the New Zealand Opera School's 2017 performance. Stage two changes are likely to occur incrementally as funds become available, with the priority of changes made being a reflection of their functional benefit, as well as their historic implication, constructional feasibility, and ultimately cost.

The major constructional alteration scheduled is the addition of a pelmet slot between the high level seating space and the ceiling void. The contract for this work is currently out to tender, along with the addition of thermostats throughout the auditorium, and louvres to the low level perimeter doors. Discussions are underway with Heritage New Zealand regarding the reintroduction of the penthouse louvres for functional and historical integrity.

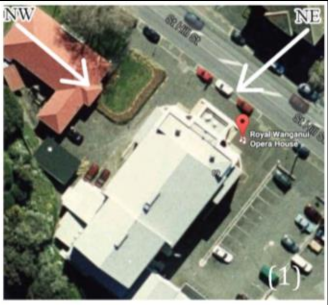
## 9 CONCLUSIONS

Natural ventilation systems often have a reduced cost in initial installation, as well as running and maintenance, over a fully mechanical heating, cooling and ventilation equivalent. Every town and city throughout New Zealand contains one, if not multiple, 100+ occupancy performance venues. Many are of similar historical value as the Royal Wanganui Opera House. Like the RWOH, as a result of recent severe earthquakes in New Zealand, many of these buildings are in the process of significant structural strengthening work. The RWOH experience has shown that the systems with which these buildings were originally designed have the potential to meet modern day standards of cooling and fresh air. The potential to restore not only the appearance but also the ventilation technology as a feature of historic preservation and earthquake strengthening is clear.

## Natural Ventilation Operation

Saturday 21st January 2017

Great Opera Moments 2017, 7.30pm – 10pm




**Predicted Weather for Sat:**
Cloudy, temp begins increasing from 11°C at 7am, to 21°C at 2pm, and decreasing to 17°C at 7pm. NW winds turn NE from 5pm to 10pm (1).

**Day leading up to Performance:**

Flush the space

- Operate all openings Fri night; ensure they are closed by 7am Sat morning.
- Limit all openings after 7am to seal the building and keep cool night air in.
- If the internal air temp rises above the external air temp, open all openings.

Limit heat gains

- Restrict all use of heaters, electrical equipment, number of occupants in the seating space, and use of stage lights where possible until the performance starts.



**Beginning of Performance:**

- If the space has remained cool, limit use of openings until performance starts.
- If the space is already warm, and if it is cooler outside or there is perceivable wind, open all perimeter doors as occupants find their seats.
- If possible, place a member of staff in the high level seating space to monitor the temperature, and begin preventative ventilation before it is too late.

Openings

☐ Ensure the butterfly dampers above the dome are in their held open position (2).
☐ Ensure the wooden slats to the vent above the high-level stage space are open (3).
☐ Ensure the windows at the back of the high-level seating space are fully opened, including behind the stage space (4).
☐ If the NW/NE wind is not strong, or is cool, open all windows fully to their slid or held back position (5).
☐ Do not open the NE facing openings in the stage roof space and seating roof space if the wind is blowing directly in (this will push warm air in the ceiling down back into the space, (6)).
☐ In event of strong NE, open all southern facing windows only.
☐ Ensure the louvered vents to the ducts in the roof space above the high-level seating space are open (7).




**Performance Interval:**

- Open all doors at low level, including fire doors, to flush the space. The more wind the better.
- If wind is occurring, open all openings to encourage cross ventilation.
- After the interval, maintain as many openings as possible depending on the success of flushing the space.

**Contingency:**

- Worst case scenario; keep all external perimeter doors open during the performance (restricted by acoustic requirements).
- Operate the extract fans above the high-level seating space at low velocity (restricted by acoustic requirements). Operate the fans at maximum speed during the interval. The smoke exhaust fan can also be operated.


Figure 9: Ventilation Guide Supplied to the RWOH Operational Team, including images of existent operable ventilation.

This project is applying the same analysis to a large, 1380 seat, brick Opera House building constructed in 1913 in Wellington. Designed by Australian architect, William Pitt, the auditorium originally had a dome like the RWOH, but in place of the ridgeline vent it possessed a sliding roof opening of some 4m x 4m free area. Like the RWOH, the Opera House in Wellington has no contemporary description of how effective was its original system. Initial analysis suggests that its original design lacked the air inlets to bring cooling air into the auditorium to match the hot air exiting through the roof. Calibration studies have established a quality assured model. Design studies are exploring ways to restore the operation of the sliding roof and sliding ceiling during earthquake strengthening in a manner that restores this historical curiosity so visitors can see the building as designed, but ensures effective cooling and fresh air delivery for 1380 people on three levels in the auditorium.

The applicability of a similar process to assess the passive ventilation potential of similar buildings is vast in New Zealand. Ultimately, with these practical case study demonstrations of the potential of CFD analysis, the aim of this research is to produce a user guide for the investigation, analysis, and subsequent recommendations for the ventilation improvement of similar large audience buildings.

## 10 ACKNOWLEDGEMENTS

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