Exploiting Natural Ventilation for Renovation of Historic Buildings in an Urban Context

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ABSTRACT: In the context of today's greater awareness of national architectural heritage, historic buildings in city centres are taken through a comprehensive exercise of restoration, renovation and re-use. Although the latter ensures a resuscitated longevity of the edifice through a new use, however this often calls for a greater energy demand per square metre, given site constraints and the limited planning articulation due to its historic listing.
This paper illustrates a study of the wind profile over flat rooftops and through the vertically proportioned streetscape in Valletta, the historic capital city of Malta, laid out on a rectangular grid iron layout on a peninsula. Wind tunnel modelling and Computational Fluid Dynamics are used to demonstrate how natural ventilation can be exploited to reduce summertime temperatures in historic courtyard buildings in Valletta, thus reducing the energy demand for cooling.

Keywords: energy, natural ventilation, passive cooling

1. INTRODUCTION

In an effort to sustain and promote cultural heritage of the built environment, most City centres are being revamped by injecting a new use to an old building in order to inject new life into established city centres around Europe.

Environmental comfort is one perk of the essential package to attract new life into the city. However this often comes at a price as energy guzzling environmental control systems are considered a must almost by default to support today's comfort norms in line with standing legislation. They also bring with them intrusive services requiring intricate layouts due to the listed almost untouchable edifice.

2. AIM OF THE STUDY

The principal aim of this study was to monitor a number of historic buildings, which typically represent the same period, namely 17th century architecture, depicting the neo-Classical and Baroque periods under the Knights of the Order of St John in Malta. These often had traditional in-built physical characteristics intended for the acclimatisation of their indoor spaces.

Apart from other dated design criteria the two most important features related to ventilation included the in-built riser stacks and the courtyard, facilitating stack and wind-driven ventilation. The narrow, vertical-proportioned streets and courtyards also contribute to this by providing cooler air and lower surface temperatures in Valletta's urban context.

2.1 Climate Overview

The Maltese Islands have a warm to hot summer with a mild to cool winter, without sub-zero temperatures. Summer days are predictably clear with a solar insolation level of 8kW/m^2 Diurnal variations range from 10-15°C, particularly in summer. The average RH of 76% is understandably high for a predominantly marine environment. It is typically windy all year round with prevailing wind directions being north-west to westerly, fig. 1 refers; only 13% of the year has no measurable air movement. [1]

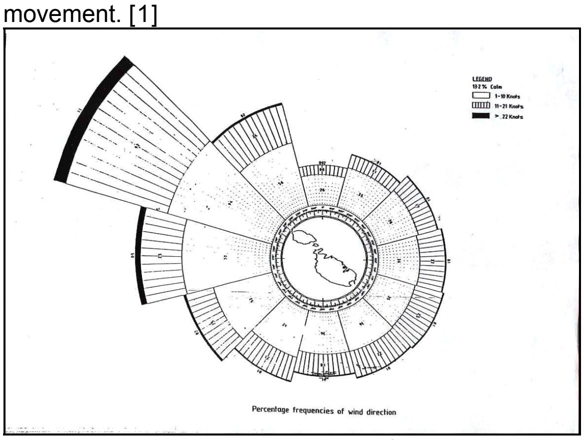


Figure 1: Wind Rose Diagram for the Maltese Archipelago, 36°N, 15°E.

In consideration of these climatic elements, environmental characteristics point towards exploiting the potential for natural ventilation. Maltese folk have demonstrated their awareness of this in their early farmhouse, serving the equally important utilitarian tools' storage, a haven for its livestock and ultimately the farmer's dwelling. As typical with vernacular architecture - 'an architecture without architects' - form followed function. Notional intuition on handling and reversing adverse weather conditions towards the better performance of the dwelling became the order of the days, today realised scientifically.

3. SELECTION OF CASE STUDIES

The final choice of four case studies (fig.2) started with a wide array of differently planned buildings in the City, a historic urban setting par excellence. The list was compiled on the basis of their age, type of construction and planning format. Courtyard buildings sum up to about 90% of the buildings in Valletta, with an introvert type of planning. The courtyard therefore serves as a 'lung' sustaining life into the building and its Mediterranean occupants' outdoor lifestyle. Such a planning characteristic, combined with narrow streets, were identified as highly influential on the building's microclimate, a quality so inherent to earlier traditional built forms. The importance of vernacular idioms, such as the courtyard is borrowed from the earlier farmhouse. [2]

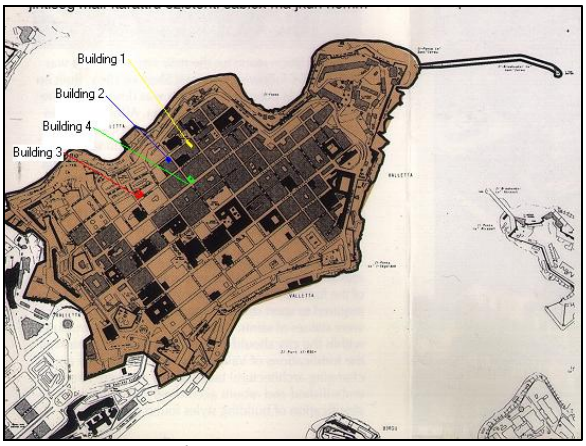


Figure 2: The four case studies within the dense urban fabric of the historic Valletta promontory

4. METHODOLOGY

4.1 Wind Tunnel Modelling

In order to comprehend further such design criteria, a study of the wind impact on natural ventilation for the four case studies was carried out by means of a physical model to a scale of 1:500. Since all buildings were within a circumscribed circle of 200m diameter, these were contained on a model of a substantial part of the Valletta peninsula.

The test facility used was the wind tunnel at the Welsh School of Architecture (WSA), an adiabatic atmospheric boundary layer wind tunnel with a working area of 4.0m x 2.0m x 1.0m high. It is suited for use with scale models of 1:100 to 1:500. This facility provides representative scale modelling of the change of wind speed with height. Within the tunnel scale models of buildings and their environs can be tested to simulate site conditions.

4.2 Objectives of experiments

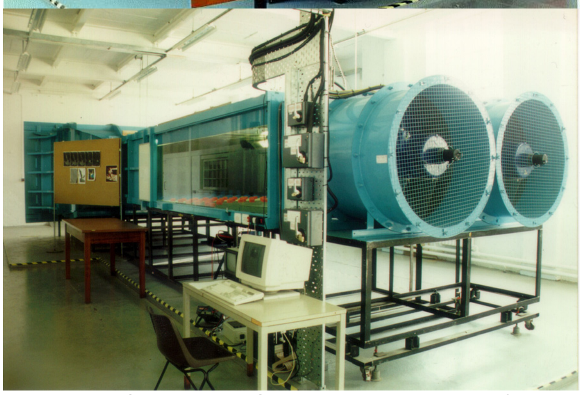
In order to achieve the principal aim of the study, a set of minor objectives were set out. These were predefined as follows:

To *quantify* the effects of wind driven natural ventilation on the original built form by obtaining pressure coefficients at the location of openings, on external elevations, riser stacks and in courtyards.

To understand the *influence* of wind effects on *flat rooftops and in open spaces from adjacent building mass,* and its effects on the overall performance of the case study buildings in question.

To investigate the *effects of the predominant wind fronts across the Valletta skyline* and their penetration into the vertical-proportioned streetscape.

To use the *external pressure coefficient* results to simulate the indoor ventilation profile through *computational fluid dynamics*.



Figures 3 & 4: The WSA wind tunnel: Front & Rear Views, Air Intake & Computer Console

4.3 Types of Experiments and Execution

Three types of experiments were carried out independently using the same model in the wind tunnel, namely Pressure Tests, Horizontal Wind Dynamics (Semolina tests) and Vertical Wind Profile (smoke tests). A CFD analysis was done separately.

4.3.1 Pressure Tests: Pressure Coefficients (Cp) were determined at the more important openings for each elevation of the case study buildings. These included street elevations, courtyards and riser stacks. Cp values were obtained for prevailing (most frequent) and predominant (strongest) wind directions. Output results helped to identify the important relationship between the courtyard size and the depth of plan. This also proved useful in predicting air movement through the building between the inner open spaces and the streetscape.

4.3.2 'Semolina' Tests (sometimes referred to as grit scouring or 'Horizontal Wind Dynamics'): Horizontal wind vector layouts on rooftops and in open spaces were obtained by spreading semolina seed uniformly as a fine grit on the model. Its scatter patterns were observed and recorded by visual aids for different wind velocities and directions. Results provided an insight into the wind impact assessment over the case study buildings and their surrounding massing in Valletta's city context. Results suggested the stronger effects of prevailing wind directions. They also indicated the wind shadow areas of the site as well as highlighting the funnelling effect of taller buildings.

4.3.3 Smoke Tests (often termed as the 'Vertical Wind Profile'): This test was performed to observe air movement across the skyline of the modelled area of the City, down to its modelled streetscape and piazzas. Different air velocities for different wind directions were tested for comparison. Visible effects of turbulence backlash effect and wind shadows were clearly identified in spots, otherwise unpredictable. With different wind directions, from the smoke tests, results indicated a flow-reversal that compared favourably with the pressure tests where both positive and negative pressures were present. Smoke dispersion in the wind tunnel also highlighted important considerations for the effects of parapet walls, belfry towers and the bastions, confronting the onshore wind front.

4.4 CFD Modelling

Computational Fluid Dynamics, or CFD modelling, is typically used to predict air movement and temperature distribution, often complementing wind tunnel modelling. Most CFD models are generated by solving a set of non-linear Reynolds-averaged, Navier-Stokes, partial differential equations that describe in a prescribed space, the variations in velocity, temperature, pressure, turbulence parameters and sometimes contaminant concentration. The DFS-AIR model [3] was employed for a complementary study, combined with on-site monitoring [4], as illustrated and reported in a separate paper by the same authors [5].

The CFD model was used to simulate conditions on still days, depicting a three-dimensional prediction of air movement through the case study buildings as a result of window openings, top of courtyard opening and original built-in ventilation stacks. The simulation was carried out for summer conditions, with an external air temperature of 30^{o}C, as extracted from meteorological data. The model gives 'steady state' predictions of air temperature and air movement at one point in time.

In order to assess the potential of natural ventilation for cooling, the output was represented on plans and sections with coloured isopleths (temperature contours) and vectors depicting air movement (velocity and direction). This was compared to separate data monitoring of the buildings' spaces on different floors [4].

5. PRINCIPAL FINDINGS

5.1 Pressure Coefficients

Following a series of test runs, three sets of simulations were carried out and mean Cp values derived. Cp values were recorded for the five more predominant wind directions, N, NW, W, NE, E. [Wind tunnel fan speed was set to 1,000 revs per minute. This is equivalent to a wind velocity of 6.70m/s, as per calibration by a centrally fixed anemometer]. Wind funnelling through streetscape and typical Cp charts are shown in figs. 5 and 6 respectively. A resume of results are reported herewith (Table 1) for the four building under review.

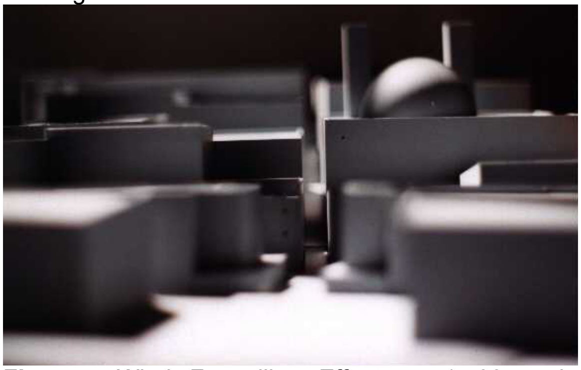


Figure 5: Wind Funnelling Effect on 1:500 scale model of Valletta

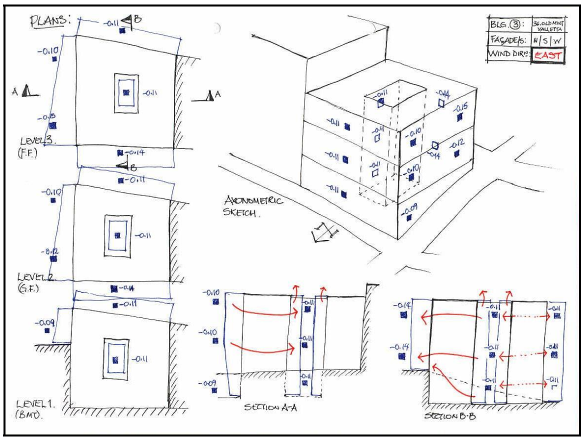


Figure 6: Typical Pressure charts for Building 3.

Table 1: Average Cp values for all four buildings with predominant wind directions for Malta

WIND:	*N*	*NW*	*W*	*NE*	*E*
Above rooftops	**-1.87**	**-1.71**	**-1.65**	**-1.71**	**-1.76**
Thro' streets	**-2.35**	**-2.23**	**-2.00**	**-2.23**	**-2.14**
BLG ONE:	**-0.27**	**-0.40**	**-0.45**	**-0.40**	**-0.13**
BLG TWO:	**-0.41**	**-0.44**	**-0.58**	**-0.44**	**-0.14**
BLG THREE:	**-0.28**	**-0.38**	**-0.49**	**-0.38**	**-0.08**
BLG FOUR:	**-0.32**	**-0.40**	**-0.53**	**-0.40**	**-0.13**
Typical Cp	**-0.25**	**-0.33**	**-0.38**	**-0.33**	**-0.11**

5.2 Horizontal & Vertical Wind Dynamics
(Semolina & smoke tests)
In order to be succinct in this 6-page paper these results are reported jointly. Following the mapping out and analysis of Cp values for all five prevailing wind directions, north, north-westerly, westerly, north-easterly and the east, only three were found to have a significant effect on the building's thermal performance, vis-à-vis its energy efficiency. These are the north, north-westerly and the westerly wind directions. Therefore the semolina and smoke tests were carried out to sensitise the whole case study site to these three wind orientations in particular.

For each of the wind directions tested, the following twinned set of typical illustrations shows the wind scouring effects (semolina tests) represented on plan, followed by a sectional image showing the wind profile across the Valletta skyline and streetscape (smoke tests), figs. 7,8 refer.

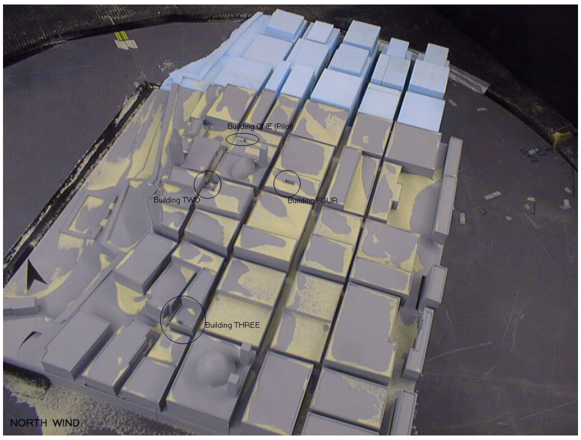


Figure 7: North wind exposure - semolina test

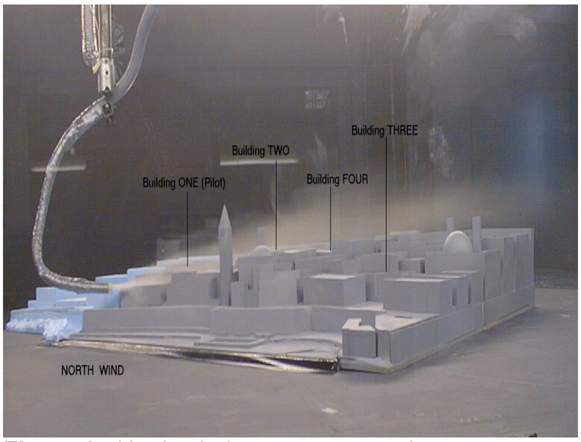


Figure 8: North wind exposure – smoke test

5.3 CFD Output results (sample)
As outlined earlier in 4.4 above, an independent paper describes the CFD study. However as results are complementary, a sample image is reproduced herewith for cross-comparison between spring/autumn (wind tunnel) and summer (CFD) conditions. Discussion follows suite.

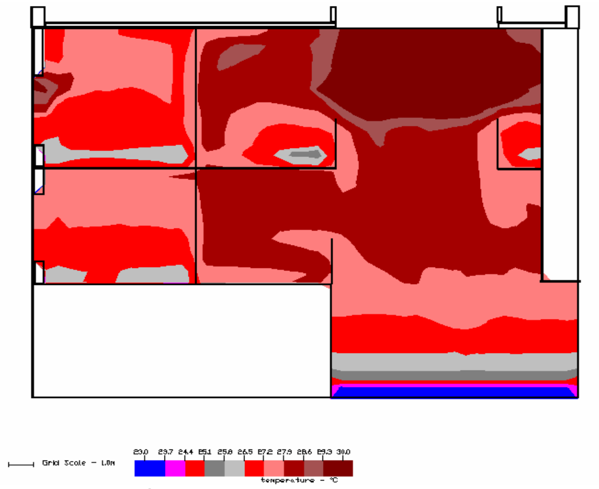


Figure 9: CFD output: section through case study building 3: air temperature distribution in summer

6. DISCUSSION OF RESULTS

6.1 Pressure Coefficients

Analysis of pressure coefficients suggested whether wind driven pressure differences are likely for a variety of wind directions. The tests are therefore not definitive but more of a guide to the performance of the buildings in use.

Pressure Coefficients (Cp) results for all the four buildings were between -0.27<Cp< -0.58 with a range of 0.31. Since near zero values were obtained, this implies that both positive and negative values may have been experienced. The marginally negative results suggest that this may be the resultant of fluctuating positive and negative values. This implies air may be incoming or outgoing through an opening, although a generally negative result was experienced throughout, signalling a suction effect, both out of the courtyards and even more upwards, from street level, the latter often narrower than the voluminous courtyards. This may possibly be due to the uplift force of the wind as it sweeps over rooftops, and also as an effect of turbulent flow between buildings, but not so much in the larger open spaces or *piazzas*.

Pressure difference fluctuations between street and courtyards suggest that there is predominantly an influx of air from the street into the courtyard, given that air movement is enhanced through open windows. It is only when recorded values of ΔCp MAX drop below +0.07 that there is an egress of air out to the street. It is to be noted however, that since three of the four buildings have more than one street elevation there could have been the combined effect of pressure differences between the streets and the courtyard, with the latter acting as the 'hub'.

6.2 Semolina Tests

As outlined in 5.2, for each wind direction three different wind speeds were simulated, stepped gradually, allowing the semolina to blow away until it settled to a uniform layout. In all, ten different speeds were tested for each wind direction. Each wind speed was left on for at least two minutes. No scientific readings were possible for this type of experiment.

However the semolina's curved patterns were recorded as different layouts on the model's rooftops, representing 'vector diagrams'. In fact notably higher building masses (such as domes and a 4-storey cinema complex) presented a shading mass for cooling effects indicating laminar to turbulent flow. This gave an indication of the convective potential cooling effect of the wind on Malta's flat roofs.

6.3 Smoke Tests

Smoke was discharged at different levels in the wind tunnel, close and away from the modelled coastline, figure 8 refers. The smoke revealed the laminar to turbulent flow across a section as the nozzle was lowered from a high level in the tunnel, exposed to 'free air', to a level closer to the buildings' rooftops and inner city streets. [This was analogous to comparing Cp values between the Pitot - static tube and the pressure taps on the model].

Visual effects, recorded on video and digital photography, further confirmed the earlier negative pressure coefficients, where a 'suction effect' was observed by the uplift force of the wind, sweeping across the Valletta skyline. Aural effects of the resistance offered by the urban built fabric on the model also demonstrated the variable effects as wind swept across the City. Dynamic & aural effects are naturally impossible to demonstrate in this paper.

6.4 CFD results

For still air conditions, the stack effect (air movement by thermal buoyancy) cannot be assessed using the wind tunnel. [In this instance CFD was considered more appropriate, particularly for indoor spaces]. Hence a separate study was carried out [5]. Although it is logically perceived that natural ventilation is predominantly wind driven, air buoyancy effects by temperature differences cannot be ignored. The wind tunnel method should provide a very good picture of the overall performance of the buildings – except on still days.

Figure 9 refers. Darker tones indicate that there is a dropdown ingress of hot air through the open courtyard, as well as through open windows, thus aggravating indoor summertime temperatures, as occupants are oblivious to such an event, as they instinctively open up the building "to let in a draft".

7. CRITIQUE OF WIND TUNNEL MODELLING

7.1 Basic Assumptions and Potential Errors

When using scale models for almost any environmental monitoring tool, errors are likely to occur due to:

Model scale & detail: Since the four buildings were modelled together on one site model, to a 1:500 scale, this did not permit fine details such as cornices, architrave and pavements to be modelled. Apart from time constraints, this would have had a minimal effect, if any on the pressure coefficient results obtained. Details omitted include different surface textures of the building fabric, (narrow) pavements, balconies, washrooms, stairwells (under 2.1m height), water tanks and dish antennae. Therefore the inability to model every detail of the physical site is not considered a serious error. The overall site context of the Capital City, Valletta and on-shore currents took precedence over almost anything else.

Unpredictability of real weather conditions: Wind speed simulations were assumed as typical air speeds for a particular time of year. Since weather data varies year to year, wind velocities cannot be accurately predicted. The direction is also never strictly in the windward side. (E.g.: if a NW wind is simulated, in reality it may be varying between north and west within one hour, with possible counter gusts from the east).

Averaging of results: Although a considerable amount of data was obtained from the set of experiments, the averaging effect may not necessarily represent particular acute conditions on extreme days, for all or any one of the buildings. However since the average values produced represent the mean pressure coefficients over a given exposure time for a particular wind direction, the values produced have fulfilled their purpose. The aim was namely to compare average pressure coefficients for each wind direction and to identify each building's highest pressure differential across a section.

Subjective choice of taps position: The location of taps on each building was intended to represent the position of the openings at each level, (fig.6). In a few instances, out of several openings at any one level, a selection of what was thought to be the more critical openings was made. This was predominantly due to the physical restraint of inserting the copper tube and rubber pipe into the modelled buildings. It would have also ended up with the number of taps being tripled. The author's selection, although based on experience of the site, is therefore still subjective.

Variations in daily atmospheric conditions: Another variation worth noting is between the different experiment days of the same week (in July 1998). When tests were repeated for the same wind speeds and directions in the wind tunnel, the relative pressure coefficients were marginally different. This is possibly attributed to variations in the atmospheric conditions, primarily air temperature, relative humidity and atmospheric pressure. It is a known fact that these are key parameters affecting aerodynamics.

Variations in climate and seasonal atmospheric conditions: Since the wind tunnel experiments were carried out Cardiff, Wales, UK, the atmospheric conditions in the lab vary considerably from the same scenario being set up in Malta. The United Kingdom and Malta have Continental and Mediterranean climates respectively. It is worth highlighting the fact that when the experiments were made, in July 1998, the week's weather was 'mild and fresh', with outdoor air temperatures around 18-20°C, considered much cooler than a typical British summer's day. Together with barometric pressure, such conditions could have had an indirect influence on pressure coefficients obtained in the wind tunnel lab.

However, across the miles, in Malta, it may be stated that the conditions on the experiment days (July'98 in the UK) were closely typical to spring and autumn conditions in a Mediterranean Island. At this time of year natural ventilation can be more relied on. Outdoor air temperatures are cooler than indoors.

8. CONCLUSION

This study has explored the potential of natural ventilation for cooling of existing (historic) buildings in Valletta. This may be fully exploited in view of:

- the topography and peninsula location of the Capital City.
- the established urban fabric (height to width ratio of streetscape) and the grid layout.
- the introvert planning disposition of most edifices (open central courtyard layout).

Based on wind tunnel experiments it may be concluded that:

On windy days the more effective to least effective wind directions were those from the W, NW/NE, N and E directions respectively. This is attributed to the promontory's geographical orientation. Other wind directions, being less prevailing and of a lower velocity all year round, are insignificant. They are typically warmer as they come across North Africa. These were thus ignored in the study.

Pressure differences indicated that there is a greater suction force across the narrow streets than over courtyards as the latter tend to be larger than the street width in most cases. However this was not the case when the building overlooks a *piazza*, where a greater uplift force was registered through the courtyard. This is naturally conditional that both windows and courtyard are unobstructed. This perhaps answers the FAQ of whether to roof or not to roof such a courtyard.

Since the weather conditions of the experiment days (early July, UK) were reasonably similar to typical May/October in Malta, it may be safely stated that the results are applicable to spring/summer conditions in Malta. This is the season when marginal cooling may be needed in an otherwise sealed air conditioned building. Hence a natural ventilation strategy may offset the energy demand for cooling.

In summer, when outdoor air temperature is higher than indoors, a different strategy needs to be adopted. Stack effect ventilation may function well enough if external openings are kept closed. If on the other hand, openings are left open "for a draft" air ingress would actually make matters worse, as CFD suggested through a separate study [5].

Semolina results suggested the stronger effects of prevailing wind directions, providing an insight into the wind shadow areas of the site as well as highlighting the funnelling effect of taller buildings.

Smoke dispersion in the wind tunnel also highlighted important considerations for the effects of parapet walls, belfry towers and the 'cliff-sized' bastions, confronting the onshore wind front. The different structure heights and variable pressure at edge vortices may have influenced the on flowing wind downstream. This is attributed to the small scale of the model (1:500). Admittedly this was limited by the working area in the WSA wind tunnel as well as the underlying scope of modelling an urban context rather than an individual building.

OVERVIEW

The original aim was namely to compare average pressure coefficients for each wind direction and to identify each building's highest pressure differential across its height and between indoor and outdoor openings, through a cross-sectional analysis.

Although this aim was generally reached through a multi-disciplinary approach, it is by no means exhaustive as tests were not definitive but more of a beacon to attract exploitation of natural ventilation. Naturally, more concrete tangible results could be obtained through on-site measurements of wind speeds over a year across the Valletta skyline and streetscape.

The four case studies chosen (historic 16th century buildings) were originally designed on basic empirical methods of the day. The general criteria included certain aspects in their design that were in many ways related, directly or indirectly, to today's more established ventilation parameters. Although in those days these were perhaps not so well understood and scientifically tested as thoroughly as today, certain building trends still demonstrated the architect's design intent beyond the exclusive functional planning of the edifice.

This is therefore an important asset to be retained and enhanced during retrofitting and refurbishment of such historic edifices, perhaps steering away from installing energy-guzzling environmental control systems almost by default, or at least minimising their use in the shoulder months of spring and autumn. This is perhaps one solid contribution of this paper to the existing body of knowledge on this subject area.

ACKNOWLEDGEMENT

This paper would not have been possible without the use of the Wind Tunnel test facility at the Welsh School of Architecture, Cardiff University, Wales. Sincere thanks are due to all the supporting staff who made these patience-trying experiments possible.

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