ASSESSING NATURAL VENTILATION AND PASSIVE CLIMATE CONTROL POSSIBILITIES IN A HOSPITAL BUILDING IN THE NETHERLANDS

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29 December 2020

ABSTRACT

While the economical, environmental, comfort and health related benefits of natural ventilation are known and proven, the choice for natural ventilation is rarely made, especially in larger buildings. This paper presents a comprehensive explanation of the driving forces for natural ventilation, the natural ventilation principles and their possible application on different typologies of buildings. Characteristic architectural elements such as solar chimneys, double-skin facades or atria are reviewed, their relevance for buildings in the Netherlands in general and for the AMC hospital in Amsterdam in specific is discussed, and the possibility to use them in combination with passive heating or cooling is assessed. Design recommendations are derived from the literature study that can be explored further in a research by design approach.

KEYWORDS

Natural ventilation, Buoyancy, Stack effect, Passive climate design, Building integrated, Solar chimney, Double-skin façade, Atrium, Academic hospital

I. INTRODUCTION

Whether it is driven by financial reasons, by the will save valuable resources or to reduce the CO2 emissions it generates, there is little need to justify the reasons for aiming at reducing the energy demand of our buildings. The building sector on its own is responsible for 23 to 47% of the global energy consumption (Chen et al, 2017, p. 386). According to Khan et al (2008), 60 to 70% of that use is to power HVAC installations, and within that post, 30 to 50% of the energy demand would be related to ventilation (p. 1527).

With the current pandemic and the questions it has raised concerning the role of climate systems in the propagation of viruses, specific attention has been brought to the risk of spreading of infectious diseases via climate systems relying on air under pressure, in other words mechanical ventilation systems (Roaf, 2020, p. 64). Years before the beginning of the Covid-19 outbreak, Schulze & Eicker (2013, p. 222) already wrote about the World Health Organization (WHO) recommending the use of natural ventilation is hospitals, especially in isolation wards, since it could yield much higher air exchange rates than mechanical systems and diminish the risk of contamination.

Yet, the choice for a natural ventilation concept, especially in a larger building, is rarely made, mostly by lack of know-how, even more so when it comes to already existing buildings. The AMC teaching hospital building in Amsterdam (NL), Europe's largest building at the time of completion in 1984, is currently facing the challenge of being in need of renovation after 35 years of existence while needing to be made ready for the inevitable energy transition ahead.

The aim of the current paper is to provide an insight on how to choose a natural ventilation system to offer satisfactory air exchange as well as passive heating or cooling in the optic of a renovation of a building of the scale of the AMC building. While the study of the possibilities to retrofit different systems on the specific building that is the AMC are more matter for an enquiry by design, this paper aims to offer an understanding of natural ventilation and how different applications can be widely compatible or not with the typology of building. To do so, we will work within the framework presented in Kleiven's doctoral thesis (2003), which describes a ventilation concept as consisting of a driving force, a ventilation principle and characteristic elements. After presenting the climatic and architectural framework set by the AMC building, we shall first focus on the natural forces that can drive a ventilation system and how they relate to the Dutch climate. We will then move on to the ventilation principles and their possible application to different typologies of buildings. Finally, we shall review the characteristic elements that can be used in a natural ventilation concept and assess the possibility to combine them with passive heating or cooling principles.

II. Framework

2.1. Climatic framework

According to Chen et al. (2017), due to the proximity of the sea, the climate in the Netherlands (especially close to the coast) can be compared with the temperate oceanic climate of the UK or the Western part of France, with moderate temperature variation throughout the year, warm summers and cool winters. As shown in figure 1, the proximity of the sea also makes for frequent and rather consequent winds, as well as for a relatively elevated and steady number of wet days throughout the year. This last comes together with often clouded skies, which combined with the latitude, result in significant variations in insolation between winter and summer, and a relatively low average clearness.

Amsterdam, Netherlands - Solar energy and surface meteorology

Variable	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Insolation, kWh/m²/day	0.68	1.41	2.55	4.07	5.36	5.53	5.44	4.59	2.95	1.64	0.78	0.49
Clearness, 0 - 1	0.32	0.39	0.43	0.48	0.51	0.48	0.50	0.49	0.43	0.37	0.30	0.28
Temperature, °C	3.07	3.29	5.60	8.61	13.12	15.72	18.27	18.42	14.98	11.37	6.78	4.11
Wind speed, m/s	7.96	7.61	7.66	6.90	6.31	6.07	6.35	6.08	6.18	6.79	7.59	7.70
Precipitation, mm	67	46	60	48	52	61	71	70	75	82	88	80
Wet days, d	18.9	12.6	17.5	13.5	14.0	13.9	13.6	13.7	15.6	16.6	19.6	18.9

These data were obtained from the NASA Langley Research Center Atmospheric Science Data Center; New et al. 2002

Figure 1: meteorological data about Amsterdam. Source: gaisma.com, retrieved on 28-12-2020.

2.2. Architectural framework: the AMC building (Amsterdam)

The Academic Medical Centre is the Netherlands' largest hospital. Built at the beginning of the 1980's, it is the embodiment of a basic philosophy developed by a critical movement within the Dutch hospital architecture in the two decades preceding the construction. Therefore, it has a quite unique layout and features. Specific of a teaching hospital is the housing of education, research and treatment facilities in the same complex, and the chosen design of several building blocks brought together into a monolith by a network of inner streets and atria was to translate a new vision on medicine (see Appendix – Figure 6). The future need for change was also taken into account with the addition of sub-floor, storey-high spaces in-between the different floors (hatched on Appendix – Figure 7), running across the whole complex, in which it is easy to access, modify and re-route all the piping systems (see appendix – Figure 8).

III. Natural Driving Forces and Climate

While it is commonly believed that the main purpose of ventilation is to provide occupants with oxygen, Hughes et al. describe it as providing an acceptable indoor air quality (IAQ). This could be assimilated to supplying fresh air and removing indoor pollutants such as odours and moisture from occupants or activity, material that can potentially be harmful (from objects or products in the space) or create discomfort. While the extraction of stale air increases with stronger airflows, too strong an airflow may in its turn create draught engendering discomfort (Hughes at al, 2012). Kleiven (2003) adds that ventilation also acts as a thermal carrier to provide thermal comfort.

Natural ventilation uses one of the only two available natural forces to create and direct the movement of air in, through and out of a building: buoyancy and wind.

3.1. Thermal buoyancy

Also called *stack effect* or *chimney effect*, thermal buoyancy is caused by differences in density between the internal and the external air. Although those differences in density *can* be the result of several factors such as moisture content, it is mostly temperature differences that will result in the density difference (Andersen, 2003, 1287).

The difference in density results in pressure differences, which can be used to pull air in and out of an enclosed space. When the air on the inside is warmer (and thus less dense) than on the outside, the inside air will rise, an over-pressure will be built up at the top forcing the air out. Subsequently, an under-pressure will occur at the bottom, pulling fresh, denser air in, as shown in Figure 2a.

3.2. Wind

Wind driven ventilation relies on pressure differences in the façade generated by the wind applying various pressures at different points of the envelope.

Figure ab shows how the pressure differences create an inward airflow on the windward side and drive air out of the building on the leeward side (Kleiven, 2003). The under- or over-pressure at a point of the building envelope is influenced by the geometry of the building, the wind velocity and direction relative to the building. The position and area of the openings on windward and leeward side influence the static over-pressure inside the building.

The pressure coefficient necessary to calculating the ventilation rate of a building is generally derived from wind tunnel measurements on reduced-scale models of the building or from computational fluid dynamics using 3D models. Those measurements are generally complex because of the amount of influencing parameters, including the surrounding landscape and buildings.

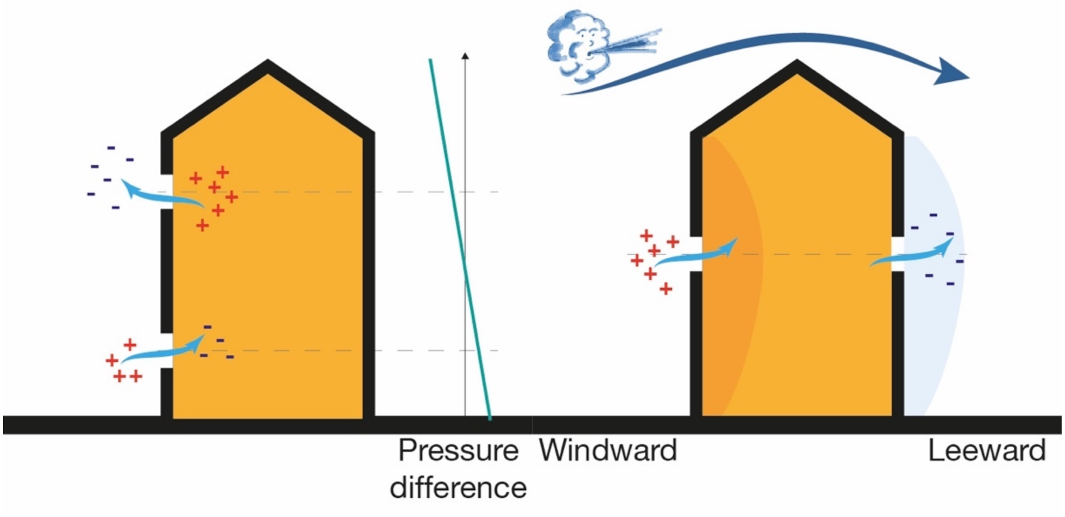

Figure 2a: Thermal buoyancy in a single space with two openings. Own illustration, adapted from Kleiven (2003)

Figure 2b: Air flow in a space with two facing openings. Own illustration

3.3. Combination of thermal buoyancy and wind

Although thermal buoyancy and wind can occur separately, they generally occur at the same time in varying proportions. Whether temperature difference or wind speed will be the dominating driving force depends on the ratio between forces and wind direction. Typically, thermal buoyancy will take the upper hand on a day with little wind, even more so if the weather is cold, which enhances the temperature difference between inside and outside. On the contrary, on a hot day when the outside temperature is close to the inside temperature, wind is more likely to be the dominating driving force (Kleiven, 2003).

Linden (1999, p. 221) describes the how the combination of a stack-driven air flow can either be reinforced or weakened by incident wind. If the opening towards which buoyancy drives the air towards the outside is on the windward façade, the overpressure of the incident wind will work against that of the stack effect, rendering the ventilation. On the opposite, if that opening is on the leeward side, the under-pressure resulting from the wind will reinforce the air extraction. Similarly, if the air inlet, driven by the under-pressure of the internal buoyancy, is on the windward side, the wind will push the air in the same direction as the stack-driven flow, hence reinforcing it.

3.4. Use of natural driving forces in the Netherlands

Based on the climatic characteristics presented in section 2.1. and on Kleiven's assumption that buoyancy will occur as soon as there is a notable difference in temperature between the inside and the outside, it is safe to assume, at the hand of the average temperatures listed in Figure 1, that thermal buoyancy can be relied upon throughout most of the year in the Netherlands. Given the apparently steady wind forces measured throughout the year, and supported the wind rose in Appendix – Figure x, showing a pre-dominance of West to South winds, wind seems to be a relatively reliable driving force as well. However, the possibility of a certain amount of windless days cannot be neglected.

IV. VENTILATION PRINCIPLES AND APPLICATION TO DIFFERENT TYPOLOGIES OF BUILDINGS

The ventilation principle describes how the airflows inside and outside of the building are connected and indicates the role of the natural driving forces to ventilate. The way the natural ventilation works, how the air is let in and exhausted, is dictated by the shape and layout of the building, especially the placement of the ventilation openings in the building envelope. (Kleiven, 2003).

There are three natural ventilation principles usually recognized, as illustrated in Figure 3: single-sided ventilation, cross ventilation and stack ventilation.

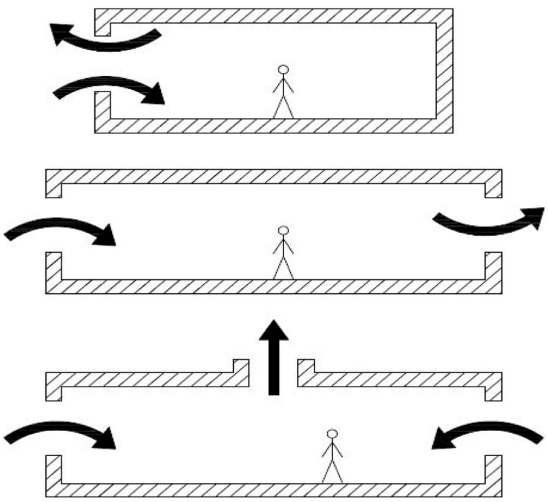

Figure 3: Schematic of the three natural ventilation principles: single-sided, cross ventilation and stack ventilation.
Source: Chenari et al. (2016) p. 1429

4.1. Single-sided ventilation

In a single-sided ventilation configuration, openings are situated on only one side of the ventilated space. The inlet and exhaust are situated on the same façade, which results in generally lower ventilation rates and a less penetrating airflow compared to other principles. In the case of a single opening, wind turbulence on the façade is the only driving force. If both openings are situated at the same height, wind can create an airflow but that flow won't be supported by buoyancy. Only when the openings are placed at different heights can the stack effect play a role in enhancing the ventilation rate.

Single-sided ventilation is typical for cellular building layouts, with each room having its own ventilation openings on one side and a closed door on the other side.

The main drawback, next to the lower ventilation rate, is the weak penetration of the ventilation air, making this principle unfit for any building where rooms have a certain depth from the façade.

4.2. Cross ventilation

Cross ventilation describes a situation in which the air flows between opposite facades through the whole depth of the building. The airflow is generally generated by wind-induced pressure differences between both sides of the envelope. The air enters on the windward side of the and exits on the leeward side generally through windows, grills or latches integrated in the façade.

This principle is particularly adapted for buildings where the air can flow across one floor, for example open-plan office spaces. Yet, with the use of overflow grills, a floorplan with some divisions can also be ventilated that way.

Within a more complex ventilation system, cross ventilation can refer to a part of the whole, when the air enters a single space on one side and exits on the opposite side without coming or going straight from or to the outside.

While flowing across the ventilated space(s), the air charges with heat and pollutants. There is therefore a limit to the depth that can be ventilated through cross-ventilation. Chenari et al. explain the rule of thumb of a maximal depth of five times the ceiling height with reduces air pressure differences on the outside and higher internal friction in long buildings (2016, p.1430). Cross ventilation is therefore better adapted to buildings with a limited depth between the facades favorably exposed to the wind.

4.3. Stack Ventilation

Stack ventilation describes a configuration in which the airflows are being drawn out of the building at a higher level. The air inlet, situated at lower levels, results from the generated under-pressure. Thermal buoyancy is typically the driving force of such a principle, although Kleiven points out that placing the outlet in wind-generated under-pressure zone can enhance the effectiveness of the stack ventilation (2003, p. 44).

Buoyancy being the primary driving force, the height difference between inlet and outlet is an important parameter, making the principle fit for virtually any depth of building, especially considering that only the outlet needs to be connected to the exterior, while the openings in an individual space can be placed virtually anywhere. It is then possible to connect individual spaces to a vertical shaft, the top of which will be connected to the outside. We shall note that at the scale of an individual space, the ventilation principle can be considered a cross-ventilation, with the air entering on one side and exiting on another (opposite or middle). (Kleiven, 2003, p.44).

By multiplying the amount of air extraction points and vertical exhaust columns, one can create a succession of cross-ventilations of sorts, allowing to ventilate very deep building sections.

4.4. Application to the AMC building

Due to the great depth of the AMC and the amount of subsequent spaces that can run up to 8 (see cross section in Appendix – Figure x), single sided and cross ventilation can be excluded as potential options for a natural ventilation concept.

V. Characteristic elements and passive pre-treatment of the air inlet

The term “characteristic elements” is introduced by Kleiven (2003) as it refers to architectural elements that are specific to a natural ventilation concept, creating or enhancing the air flow making use of the natural driving forces. Subsequently, those elements, absent in mechanically ventilated buildings, differentiate naturally ventilated buildings.

Kleiven (2003) however notes the following:

> Natural ventilation can be realised without the use of dedicated ventilation elements. The building itself doubles then as a ventilation element, which could be named “building integrated element”. In this case the building, as a result of its design, is capable of harnessing the natural driving forces and to direct the ventilation air through its spaces without the need for dedicated ventilation elements. (Kleiven, 2003, p. 52)

We can therefore distinguish two different categories of characteristic elements: the dedicated, “added” elements and the building integrated elements.

5.1. Dedicated elements

5.1.1. Wind scoops

Wind scoops are generally roof mounted devices designed to intercept part of the wind flow and direct it into the building. The choice generally is for positioning on the roof since it is where the airflow is the strongest and the most stable (Kleiven, 2003). Depending on the dominating wind direction (if there is one), one can choose for either a fixed or omnidirectional wind scoop. Another drawback of this specific system is that it is entirely depending on the wind’s strength, potentially scaling from not functioning to discomfortable draught.

5.1.2. Wind cowl

Based on a similar principle but faced against the wind, is the wind cowl. The wind flowing along the element will not penetrate the building but create an under-pressure, thus siphoning the air out of the building. The Venturi wing or Ventec roof is a variation of the wind cowl, making use of a specific element, often called the wing due to its working similar to that of a plane’s wing, to enhance the under-pressure. By increasing the wind’s speed on top of the wing, an under-pressure is created at the bottom of the wing which is placed above the duct of the cowl.

5.1.3. Wind catcher

Khan et al. (2008, p. 1593) describe the wind catcher as a wind scoop and cowl in one. On the windward side, wind is drawn into the building, while the stale air is extracted on the leeward side. Although the system relies on two separate opposed shafts for air intake and outlet, wind catchers generally are made of 4 quadrants that can act as air intakes or extractors depending on the wind direction. That way, they are less sensitive to wind changes.

5.1.4. Wind tower

On the edge between added and integrated elements, we find the wind tower. According to Khan et al. (2008), a wind tower functions according to the same principle as a wind catcher, but at a much larger scale and applied in a generally separate architectural element, either on top or next to a building. Besides the scale, the main difference with a wind catcher is the added use of the longer drop of the air inlet to pre-cool it before directing it inside the building. The air is scooped by the top of the tower and directed down through its body, where it is cooled by the thermal mass that has been cooled during the night. The warm and stale air finds its way through natural buoyancy towards the second conduit of the tower, at the top of which the wind-generated negative pressure will siphon it out. This system has been used for centuries in the vernacular architecture of the Middle East, but the principle has inspired more modern passive designs, such as certain uses of a double-skin façade, earning it its place so close to the integrated elements.

5.1.5. Drawbacks of dedicated elements

The elements listed here are generally roof-mounted elements. Due their rather small scale, they generally do not have the necessary height to effectively make use of buoyancy and rely only on wind. In this very feature lies their first main drawback: they do not function in the absence of wind. (Kleiven, 2003). In addition, the conclusion from the previous section that the AMC building is not suited for single-sided or cross ventilation excludes such systems from the list of possible main elements for the natural ventilation of our hospital. However, their specific working and possibility to be adapted on many places on a roof could be exploited to use such elements in support of a main stack-driven system.

5.2. Integrated elements

5.2.1. (Solar) chimney

In its basic functioning, a chimney makes use of thermal buoyancy to extract air from a building and expel it at the top of the chimney. A solar chimney utilizes solar radiation to increase the temperature and the density difference between bottom and top of the chimney. While a plain chimney mostly relies on its height to beneficiate from a significant enough density drop, the added value of the solar heating is that it allows to reduce the height of the air column to achieve comparable results. (Zhai et al., 2011)

Plain chimneys have the advantage that they can function regardless of the solar energy or of their location in the building, as long as the top of the chimney is high enough compared to the rest of the building, as long as the temperature at the bottom of the chimney (cq inside) is superior to that outside at the top. Solar chimneys can be either vertical or inclined, making it possible to integrate them either in a wall or on the roof (Zhai et al. 2011). Solar exposure is however crucial for full efficiency, although the natural buoyancy due to inner temperature will always bepresent. Placing a wind coil at the top of such a chimney can allow the wind to enhance the airflow by creating a complementary under-pressure (Kleiven, 2003), which can compensate for the lower airflow that a reduced-sized solar chimney will yield when sun exposure is low.

Zhai et al. (2011, p. 3762-3763) expose the possible use of solar chimneys with passive heating or cooling. Passive heating using the sun in a similar way as for inducing air movement can be applied in a combination of solar chimney and Trombe wall in the sun-exposed façade, but because of the chimney being designed for air exhaust only, the pre-heating of the incoming air cannot be gain directly from it. While the cooling capacity primarily rely on a higher ventilation rate to exhaust the excess heat, the fact that a solar chimney induces the air flow on the exhaust side allows the air inlet to be directed through several possible heat exchangers on its way in, such as earth-air (air inlet through an underground pipe) or evaporative cooling. We can also note that the more sun energy is available (and therefore the higher the need for ventilation) the stronger the stack effect will be.

5.2.2. Double skin façade

In a buoyancy-driven extraction configuration, the working of a double-skin façade is comparable with that of a solar chimney. What makes the double skin façade such an interesting architectural element is however the diversity of its possible uses.

As described by Ding et al. (2005), a double skin façade can be used as well as inlet as as exhaust. The air in the intermediate space is heated by solar radiation and can be, according to the configuration and the climate, let into the building after being pre-heated or let to rise under the stack effect, generating an air flow to drive air extraction. With the combination of a generally entirely glazed wall and great height, the thermal buoyancy yields good airflows even without a lot of solar energy, making it applicable is temperate climates, in which the pre-heating of the inlet air is also profitable a great part of the year.

5.2.3. Atrium

The use of an atrium as an architectural element as well as as a climate control element is nothing new. The romans already used it as a climate modifier and gave it the name we still use. Modern atria however are typically covered in glass. An atrium is generally centrally laid in a building, interconnects most of the spaces and connect them with the environment. That they play a role in the ventilation of the building seems therefore evident. In their paper on natural ventilation in atria, Moosavi et al. (2014) describe natural ventilation in an atrium as driven mainly by thermal buoyancy, although wind can enhance the performance by increasing the over-pressure at the lower inlet as well as the under-pressure at the higher exhaust.

Atria can be utilised in many ways in a natural ventilation system, drawing significant advantage of the following features: they are central and connected to most spaces of the building (hence suitable for providing or extracting air from those spaces), they are generally several stories high (favourable for buoyancy) and glass-covered, which in the case of air supply, offers pre-heating. The glazing represents at the same time the main drawback as it may induce very high temperatures on hot days or in hotter climates. (Kleiven, 2003)

When used for central air inlet, atria rely more on the wind as driving force, and to avoid creating a single-sided ventilation configuration between the atrium and the adjacent spaces, it will require an extraction principle. When used as an exhaust, the buoyancy will likely be the dominating driving force, and the temperature difference between the air from the adjacent spaces and the outside will in many cases be sufficient.

5.2.4. Application of building integrated characteristic elements

We should first note that while the characteristic elements have been studied separately, they rarely operate alone, especially in larger buildings. One element generally is used to create the supply while another element takes care of the exhaust, or while one element is mainly responsible for the airflow, other elements may help increase it.

In a climate such as in the Netherlands, although the differences between the summer and winter climates are moderate, a building finds itself in need of heating as well as of cooling throughout the year. Elements such as atria and double-skin facades, that can be utilized either in air supply as exhaust, can also be combined in a system that would operate in opposite directions depending on the weather. While this may not have the largest effect on the airflow, it would allow to use other properties of each element to treat the air entering the building.

VI. CONCLUSIONS

This paper has first presented the natural driving forces upon which natural ventilation can rely. Given the moderate climatic conditions of the Netherlands, both wind and natural buoyancy seem to be reliable driving forces, although stack effect on its own will not be sufficient on the warmer days of summer (inner temperature potentially equal or higher than outside), and wind-driven ventilation will not operate on windless days.

We further presented the ventilation principles and concluded that single-sided ventilation and cross ventilation, due to the limit in building depth they are able to ventilate (especially single-sided) would not be suitable for a building such as the AMC. As an exception to this statement, the bed towers at the centre of the hospital are the only part of the building with low depth from the façade.

Based on this statement, we explored the integrated characteristic elements that can be used in a large building, namely the solar chimney, the double skin façade and the atrium. Except for the chimney which is exclusively an exhaust system, those systems can be used either as inlet or as exhaust.

Given the varying climatic conditions and the scale of the AMC building, a combination of several elements seems the best course. Since the AMC already has several atria and façades in need of renovation, it would make sense to explore combinations with those elements in a system that would operate in opposite directions depending on the needs in the design process to come. One could think of a double- skin façade acting as a solar chimney for extraction on warmer days, with an atrium acting as a ventilation chamber to distribute air brought in through the ground (therefore tempered), while a winter configuration could see the double-skin pre-heating the fresh air before letting it in, while the stale air would exit through the atrium thanks to the stack effect.

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APPENDIX

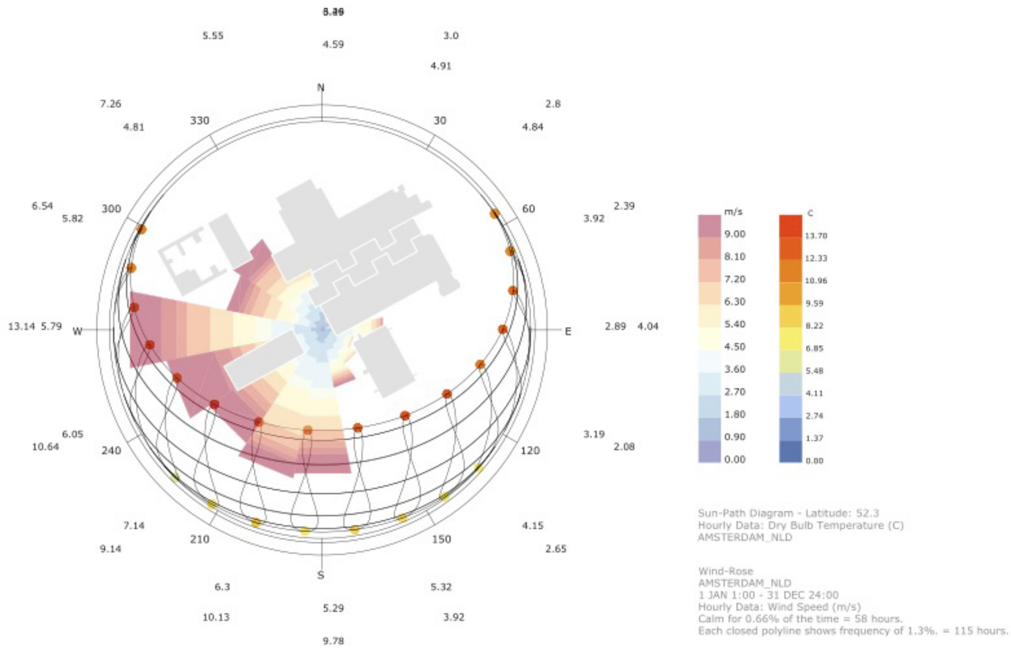

Figure 4: Wind rose and solar diagram of Amsterdam (NL) projected on the AMC
Source: Dalinghaus (2018, p. 3)

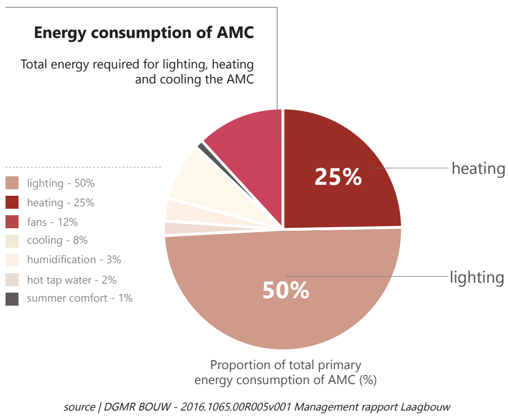

Figure 5: Energy consumption of the AMC
Source: DGMR Bouw (2016)

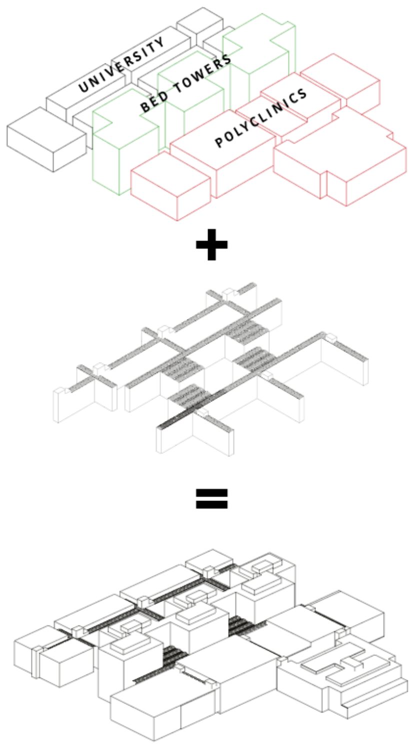

Figure 6: Composition of the AMC: 12 building blocks grouped with 3 major functions, interconnected by intersticial spaces (streets and atria) to form the so-called 'monolith'
Source: Anatomy of the AMC (TU Delft)

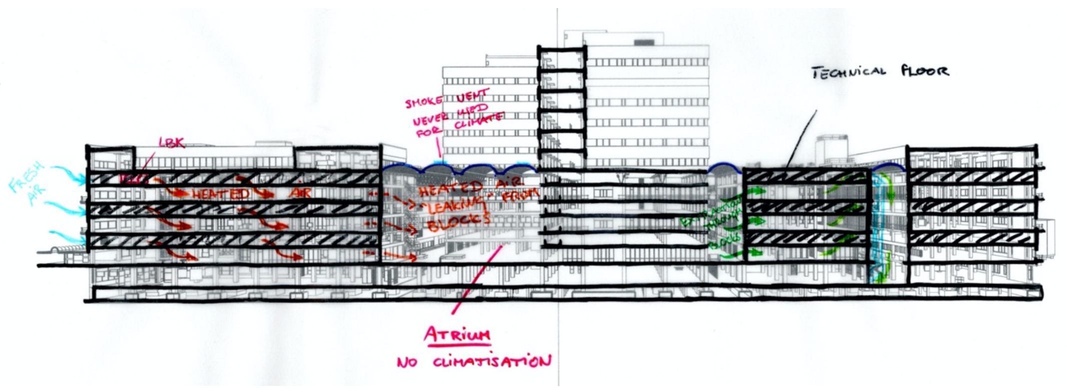

Figure 7: Cross section of the AMC with explanation of current ventilation system
Source: own work based on drawing from Anatomy of the AMC (TU Delft)

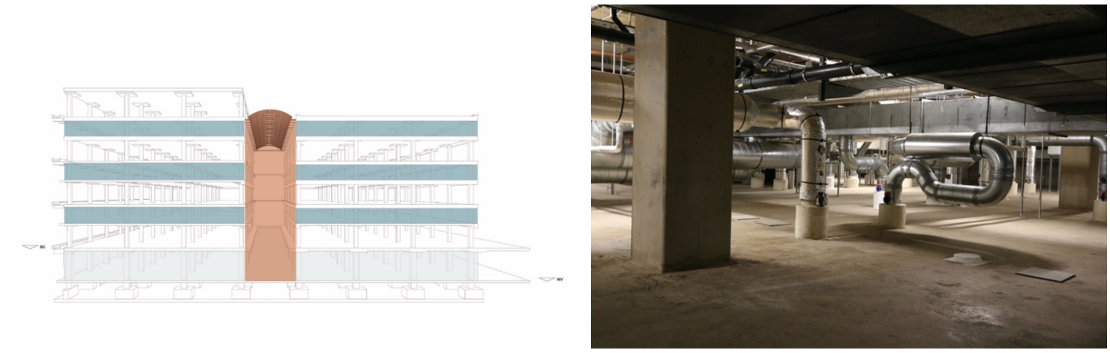

Figure 8: Left: partial cross section of the AMC showing the sub-floors and an inner street.
Source: own work based on drawing from Anatomy of the AMC (TU Delft)
Right: one of the technical sub-floors. Source: Own picture, 12 July 2018

Table 1: Summary of characteristic elements, the main driving force and ventilation principle they rely on, their possible application and suitability for a temperate climate based on functioning in the absence of sun or wind.
"++" means a given element will yield a comparable airflow in the absence of sun or wind ;
"+" means a given element will still yield some airflow but with a diminished efficiency ;
"-" means a given element will not operate in the absence of its driving force.
Source: own work.

Element	**Driving force**		**Principle**			**Application**		**Climate**	
	Wind	**Stack**	**Single sided**	**Cross**	**Stack**	**Inlet**	**Outlet**		
Atrium	v	v	v	v	v	v	v	++*	++*
Air inlet	*v*			*v*	*v*	*v*		++	+
Air exhaust		*v*		*v*	*v*		*v*	+	++
Double skin facade	v	v	v	v	v	v	v	++*	++*
Air inlet	*v*		*v*		*v*	*v*		++**	+
Air exhaust		*v*		*v*	*v*		*v*	+	++
Chimney		v			v		v	++	++
Solar chimney		v			v		v	+	++
Wind scoop	v			v	v	v		++	-
Wind coil	v			v	v		v	++	-
Wind catcher	v			v	v	v	v	++	-

*= depending on dominant driving force and application, the element will be less efficient when relying entirely on secondary driving force
**= the air supply will still be sufficient but without pre-heating