The Use of Scientific Calculations in Design Procedures for Heating, Ventilation, Daylighting and Acoustics from the Eighteenth Century to the mid-Twentieth Century

Bill Addis

The use of scientific calculations to predict the performance of building services systems and the internal environment of buildings dates from the development of the respective branches of experimental physics, mainly in the eighteenth and nineteenth centuries. Such calculations, whether in the physics laboratory or the building design office, depend on the scientific concepts that form the basis of the theoretical framework of those sciences. With these concepts there came also the variables that can be measured and the instruments for measuring them.

For heating, the key concepts and variables are temperature, heat and enthalpy (the heat content of air); for ventilation, the parameters of fluid flow (especially speed and pressure), humidity and various measures of air-freshness. Although it was possible to make judgements about the intensity and frequency of light and sound in the nineteenth century, reliable measurements were only made possible with the development of devices in the twentieth century that transformed light and sound into electrical signals.

The development of each branch of scientific building design followed a similar pattern. First came empirical rules, some based on scientific principles, others simply on what was known to work. Then came the use of *relative* measures that allowed aspects of building performance to be scaled by factors of perhaps +/- 10 to 15% with the size of room, building or plant and equipment. Then both scientists and designers made use of physical scale models to predict the performance of a full-size building from tests on a model built at (say) one-tenth scale (Cowan et al. 1968). The use of such scale models allowed many issues of great complexity to be addressed without a full understanding of their precise scientific behaviour. Finally, as the various aspects of the complex processes came to be fully understood by scientists, it became possible create mathematical models that fully represented the variation of behaviour with scale, and allowed the reliable prediction of *absolute* values of the various parameters.

First let us review some of the graphical and numerical methods devised to make the engineer's design calculations easier and quicker to perform (before the use of computers).

METHODS OF CALCULATION

Arithmetic

The use of Hindu/Arabic numerals (which included a symbol for zero) spread across Europe from the Moorish Empire in the South of Spain and had largely replaced the use of Roman numerals by the end of the thirteenth century. However, it was only with the widespread use of decimal fractions (‘decimals’) during the late sixteenth century that the process of calculation became as easy as we perceive it today (Cajori 1893). For this reason, until the early seventeenth century, calculations were made using geometrical constructions if possible. One of the first uses to which sixteenth-century mathematicians put decimal calculations was compiling accurate tables of squares, cubes, square and cube roots, and the trigonometric functions – sine, cosine and tangent. The ease and speed with which calculations could be performed were both further improved over the following two centuries by the invention and adoption of symbols used to represent the various mathematical operations such as +, -, □□x^2, x^3, x^{-1}, $x^{½}$, □^{3}□and so on (Cajori 1928). Many rival forms of notation were devised by different mathematicians and each promoted his own as better than that of his rivals, rather like the authors of rival software programs for word-processing or spreadsheets in the modern era. The eventual ‘winner’ was decided by the users.

Logarithms

Logarithms were invented by the Scottish mathematician John Napier (1550-1617) and published in 1614 (Aspray 1990). Using tables of logarithms, the processes of multiplication and division are reduced to the simple addition and subtraction of figures, which were quicker to perform.

The slide rule

The slide rule has two logarithmic scales that allow multiplication to be performed by the addition of two lengths. It was invented within a few years of the first tables of logarithms being published. During its first century or so the slide rule was used by surveyors and ship’s navigators, and probably by ship designers; but we do not know how much (or little) it was used by civil, building or mechanical engineers. We know it was being so used in the 1780s because James Watt (1736-1819) manufactured and sold slide rules known as “Soho scales”, after Boulton and Watt’s Soho works in Birmingham. The widespread adoption of the slide rule as the engineer’s calculating tool was due to the French engineer Amedée Mannheim (1831-1906) who in 1850 standardised the various different scales on the slide rule and improved the design of the cursor, the hairline marker that enables the scales to be set and read more accurately (Cajori 1909). From the following year the use of the slide rule was taught in all French schools of military and civil engineering. It remained the engineer’s indispensable tool until 1971 when it was replaced by the hand-held electronic calculator. A practised slide rule user could perform both simple and complex engineering calculations at about the same speed as a calculator user.

Graphical calculation methods

Despite the relative ease that the slide rule brought to calculations, graphical methods of calculation remained popular. (Indeed, it could be argued that a slide rule is a graphical method, since it involved the addition or subtraction of two lengths). In 1843 the French civil engineer Léon Lalanne (1811-1892) devised his “universal calculator” - effectively a sheet of log-log graph paper on which was also drawn a diagonal grid (Lalanne 1846). This allowed the product of any two numbers to be read off almost instantaneously.

From the earliest days of tradesmen's guides (e.g. carpenters) in the sixteenth century, the relationship between dependent variables was usually shown in tables of values. The use of graphs to represent such data in visual form began in the eighteenth century but became popular only from the mid-nineteenth century. The first representation of three sets of data on a two dimensional diagram was by the French geographer Phillipe Buache (1700-1773) who created a contour map of the depth of the English Channel in 1737 and the idea was soon used to show heights of land above sea level. This use of contours was employed by Lalanne in 1843 to representing the ambient temperature at a place for every hour of the day and during each month of the year. In the same year he devised the "wind rose" which shows the frequency distribution of wind directions at a certain place. Both charts are still in widespread use by building services engineers today.

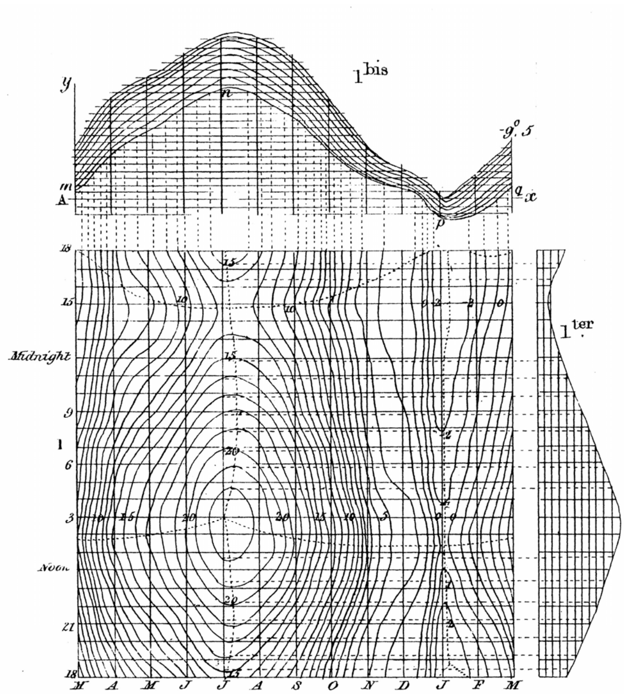


Figure 1. Contour plot of annual temperatures (Lalanne 1846, Plate 1)

Graphs showing the relationship between three variables came into widespread use in design procedures in all branches of engineering during the second half of the nineteenth century and their use survives today. The most famous in building services design is the Mollier diagram, devised by the German physicist Richard Mollier (1863-1935). In 1892 he created the chart showing the complex thermodynamic relationship between the heat content (enthalpy) of air, the proportion of water vapour and the temperature. Similar Mollier diagrams were soon used by the designers of all types of heat engines – steam and internal combustion engines as well as refrigeration plant using various refrigerants including ammonia and carbon dioxide. These diagrams were soon used by engineers throughout the world.

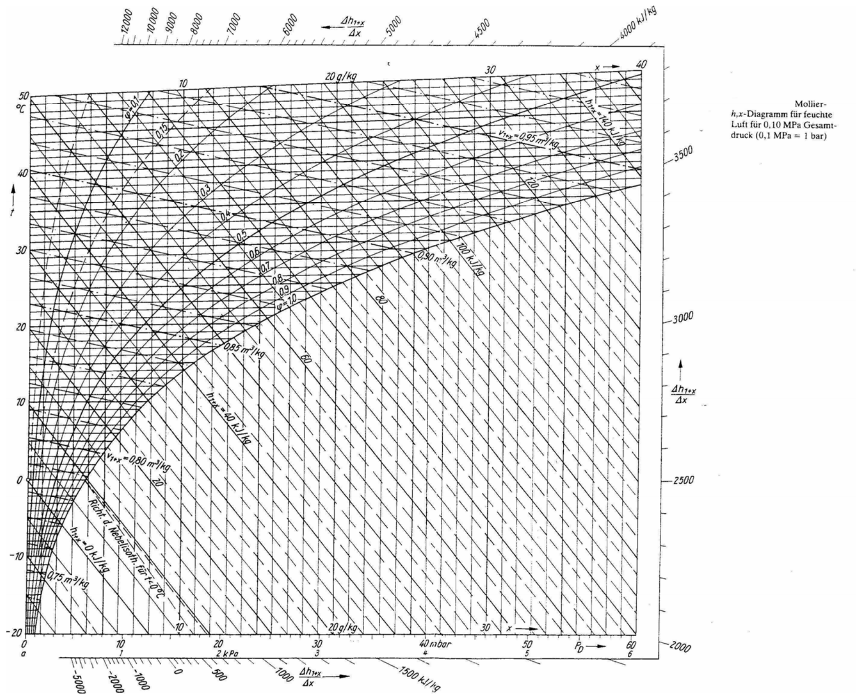


Figure 2. Mollier diagram for humid air (Martin Luther University, Halle Wittenberg)

Nomography

The most sophisticated and ingenious graphical calculating device developed for engineers was the nomogram. This technique was developed by the French mathematician Philbert Maurice d'Ocagne (1862-1938) in the 1880s. Its purpose was to solve all equations of a given type by means of one diagram. A nomogram enables, in principle, any number of variables to be handled and the sequential mode of their operation resembles the use of sequential operations that form the basis of a computer program. A nomogram consists of a number of scales drawn parallel on the page at carefully calculated distances. Each 'input' has a separate scale. By drawing lines between the values on the input scales a point is created on the 'output' scale which is the solution to the equation. Like the scales on a calculation-specific slide rule, a nomogram encapsulates what, to many engineers, would have been complex engineering science (d'Ocagne 1899). It could also incorporate empirical data such as material properties. In the early days of reinforced concrete, they were ideal as a means of enabling engineers to design simple structures using the new material. Nomograms formed part of design methods in many branches of building engineering well into the 1980s.

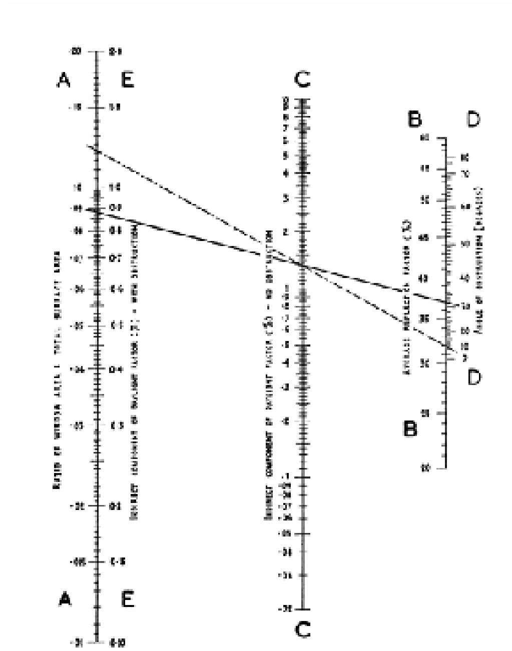


Figure 3. Daylight factor nomogram (Building Research Station)

Mechanical calculators

Mechanical calculators were first developed for use by banks and accountants and were restricted to addition and subtraction. In the 1920s machines were developed that enabled numbers to be multiplied by repeated addition and the mechanical movement of the entire mechanism one decimal place to the right by up to ten decimal places. One of the most popular brands was Facit, known as the Hand Facit or Electric Facit according to whether the laborious process of rotating the machine was performed by hand or electric motor. A remarkable degree of miniaturisation of a hand calculator was achieved in the Curta Calculator, patented in 1951, which calculated to eight-figure accuracy in a hand-held device smaller than a coffee mug.

HEATING & VENTILATION

Drivers

Horticultural buildings were among the first to have heating and ventilation systems that are clear ancestors of modern systems (Donaldson & Nagengast 1994). Hot houses were warmed by both steam and hot water from the early eighteenth century.

The centralised heating of large buildings began in the mid-eighteenth century with buildings in which large numbers of people congregated, such as town halls and theatres. At the same time, early textile factories required centralised heating systems, not for the benefit of the workers but to prevent the temperature of the cotton and wool fibres falling below 60°F when they become too weak and brittle to be handled by the spinning and weaving machinery.

Long before the seventeenth century it was recognised that fires help the ventilation of rooms as air is drawn in to replace the hot air forced up chimneys. The ventilation, however, came as a by-product of the heating system; with no fire, such as in summer, there was little ventilation. This same effect was used by Christopher Wren in the 1690s to provide forced ventilation independently of the heating system when he undertook the refurbishment of the Houses of Parliament. From the mid-eighteenth century forced ventilation using heat as the motive power was used increasingly in many types of building where large numbers of people were collected – hospitals, prisons and theatres, and also the lower decks of warships (Bruegemann 1978). Various methods of natural ventilation were also used successfully, especially in hospitals and prisons.

Mechanical ventilation using hand-powered fans had been used in mines since the sixteenth century at least and was used in some buildings in the eighteenth century, including the Houses of Parliament, and later. Mechanical ventilation became common during the nineteenth century when small steam engines and, from the 1890s, electric motors and internal combustion engines became available to drive the fans.

Effective refrigeration plant was first developed for the storage of food from the 1840s. It was used to cool buildings in hot climates from the 1870s when it was used to manufacture 'artificial ice' on a large scale to replace ice imported to Europe from Norway and North America. Blocks of ice were placed in the air inlet ducts to cool the air; Madison Square theatre, New York used 4 tons of ice each evening in the 1880s. The first installation of refrigeration plant for direct cooling of buildings was done by the German engineer Carl von Linde (1842-1934) in 1874, and spread rapidly throughout countries with hot climates.

The first successful installation of humidification in a textile factory in North Carolina was by Stuart Cramer (1867-1940) in 1904-05. This depended on the hygrometer he devised to allow control of the moisture content; Cramer also coined the phrase 'air-conditioning' where both temperature and humidity are controlled. After its use in textile and tobacco industries, it was introduced sequentially into buildings for public use, first cinemas and theatres in the 1920s, then hotels and apartment blocks, and lastly offices in the 1930s.

Design in pre-scientific times

The requirement of any design method or procedure is that it should enable the building designers to predict the performance of buildings *before they were constructed*. They had to answer vital questions such as how large a boiler or steam engine would be needed to drive a heating or ventilation system in a new building. The difficulty was that different aspects of heating and ventilation design involved physical phenomena that, even today, are extremely complex – heat transfer from hot pipes to air in a furnace or a room; the mixing of heated air with cooler ambient air; the driving of ventilation by means of the stack effect, and so on. Generally speaking design rules were very simple such as relating the size of a fire or boiler to the number of rooms to be heated. As the understanding of the nature of heat and heat flow grew, so the roule began to incorporate some scientific basis. One example of such a design rule for calculating heat loss from a green house, was given in the Transactions of the Royal Horticultural Society (1861) "Every superficial foot of glass is capable of cooling one and a quarter cubic feet as many degrees per minute as the degree of the external atmosphere falls short of that within the building".

The scientific concepts

The heating, ventilation and air-conditioning of buildings is underpinned by the fundamental understanding of the physics and chemistry of the atmosphere and, after the contribution of the French physicist Sadi Carnot (1796-1832), the entire subject of thermodynamics, as well as the fundamentals of fluid flow. Here we can present a selective list only:

- Temperature – Galileo, 1592; Fahrenheit, 1715
- Heat (as distinct from temperature) Joseph Black (1728-1799), 1760s
- Latent heat of evaporation – Black, 1760s
- the thermal conductivity of materials – c.1800
- Heat as a form of energy not caloric Benjamin Thomson (Count Rumford) (1753-1814),
- the rate at which mechanical work (or energy) is converted into heat
- understanding of how dew forms William Charles Wells 1814

To these developments in thermodynamics must be added the understanding of the constituents of air and the means by which diseases were spread. By 1800 a modern scientific explanation had largely replaced the earlier concepts of miasma and 'foul air':

- constituents of air – Robert Hooke, 1670s, Joseph Black, 1750s, Joseph Priestley & Antoine Lavoisier 1770s.
- establishing the link between air quality and spread of diseases – 1770s
- scientific understanding of the benefits of fresh air – from 1750-80s
- establishing the quantity of fresh air per hour needed by a person – by 1810

From its first appearance around 1700 to the 1820s the steam engine had progressed entirely without help from science. In 1819, at the age of just 23, the French physicist Sadi Carnot (1796-1832) wrote his paper "Reflections on the motive power of heat" which laid the foundation upon which the new science of thermodynamics would later be built. Of the steam engine builders he observed:

> "their theory is very little understood and attempts to improve them are still directed almost by chance. The question has often been raised whether the motive power of heat is unbounded, whether the possible improvements in steam engines have an assignable limit – a limit which the nature of things will not allow to be passed by any means whatever, or whether on the contrary, these improvements may be carried on indefinitely." (Carnot 1824)

In his paper, which was based upon the caloric theory of heat, he described the heat engine cycle and predicted its reversibility (i.e. refrigeration). After remaining virtually unknown for a quarter of a century, the significance of Carnot's work was recognised by two scientists in the 1840s – William Thomson, later Lord Kelvin (1824-1907) and Rudolf Clausius (1822-1888), both of whom still argued on the basis of the caloric theory of heat (the caloric theory of heat was finally laid to rest in the 1850s). Together they established the modern science of thermodynamics, including the 1st and 2nd laws of thermodynamics and the practicality of reversing the heat engine cycle to create the refrigeration cycle and the heat pump. In fact, the first refrigerators using vapour compression cycle had been made in the 1840s but, as with the steam engine, improving the effectiveness and efficiency of the refrigeration process had quickly reached the limit of what was possible without using the fundamental concepts of thermodynamics. The work of Thompson and Clausius allowed this barrier to be bridged.

The final stage in developing the science of heating, ventilation and air conditioning came in the 1890s when Mollier invented the concept of 'enthalpy' (Wärmeinhalt) as a measure of the total energy contained in a thermodynamic fluid – the steam in a steam engine, gases in an internal combustion engineer, or the refrigerant in a refrigerator or chiller. Mollier produced enthalpy-temperature charts for all the main thermodynamic fluids during the decade 1894-1904. The Mollier Diagram for air/water vapour made the design of air humidifiers a practical possibility for 'ordinary' engineers.

Scientific design methods

By the 1810s the quantity of fresh air per hour that a person needs had been established and design calculations quickly followed that estimated the total quantity of fresh air that would need to be introduced into a building occupied by many people, such as a prison or hospital, to maintain satisfactory air quality. The demand could then be matched to the means of supply, both the capacity of ventilation fans and the size of ducts needed to introduce fresh air into rooms and to exhaust "foul air" from them. Although it was not yet possible to define quantitative measurements of other aspects of the engineering performance of buildings, such as humidity, acoustics and lighting intensity, rational guidance of a qualitative nature was already being formulated and adopted by designers.

The first author to approach the design of heating and ventilation systems in a scientific manner was Thomas Tredgold (1788-1829) (Tredgold 1824). He dispelled the current belief that the quantity of heat needed was directly proportional to the volume of the space being heated. He offered a more rational design method based upon the fact that the heat loss from the room was the most important factor and this depended on the area of glazing, the ratio of the surface area of the room to its volume, and the temperature difference between the outside air and the temperature desired inside. He checked these principles using simple experiments on the cooling of hot water cylinders, using his modest knowledge of physics most effectively. On the ventilation of buildings, he advocated the importance of seeking and removing the causes of foul air. He also based the amount of ventilation needed on the physiological needs of people, estimating these as a quarter of a cubic foot per minute to provide sufficient oxygen and three cubic feet per minute to remove the water vapour exhaled. To this he added an amount of air needed to sustain the burning of candles for lighting giving a total requirement of about 4 cubic feet per minute per person (about 114 litres per minute). Tredgold's book was highly successful and served the needs of practising engineers well (Billington & Roberts 1982). It was translated into French and German, ran to three editions in English and was still being recommended as essential reading in the 1880s. Most subsequent writers on heating and ventilation based their approach on Tredgold's, and he was credited as being the first author who brought together engineering, the needs of human physiology and the idea of human comfort. One of the first large buildings to be designed using Tredgold's scientific approach were the new Houses of Parliament, built in 1841-54 whose sophisticated heating and ventilating system was designed by the Scottish chemist and engineer David Boswell Reid (1805-63) (Reid 1844, Donaldson & Nagengast 1994). Despite its complexity the system worked successfully for nearly a hundred and thirty years.

The first comprehensive application of the principles of thermodynamics to the heating and ventilation of buildings was undertaken by the German engineer Hermann Rietschel (1847-1914) in the 1880s. In 1887 Rietschel founded his "Testing Station for Heating and Ventilation Equipment" in 1887 and published his "Manual for the Calculation and Design of Ventilating and Heating Installations" in 1894. (Rietschel 1894).

In the early 1890s Mollier used his new concept of enthalpy in design charts for engineers that enabled them to study the thermodynamic state of any fluid throughout a heat (or cooling) engine. Mollier diagrams were soon used by engineers designing steam engines, internal combustion engineers, refrigerators, heat pumps and plant used to 'condition' the air in factories and, later, buildings used by the public. In 1908 Willis Carrier (1876-1950) prepared his own, simplified version of the Mollier Diagram, calling it the psychrometric chart. The American Society of

Heating and Ventilating Engineers used Carrier's chart to demonstrate the idea of the 'comfort zone' in 1924.

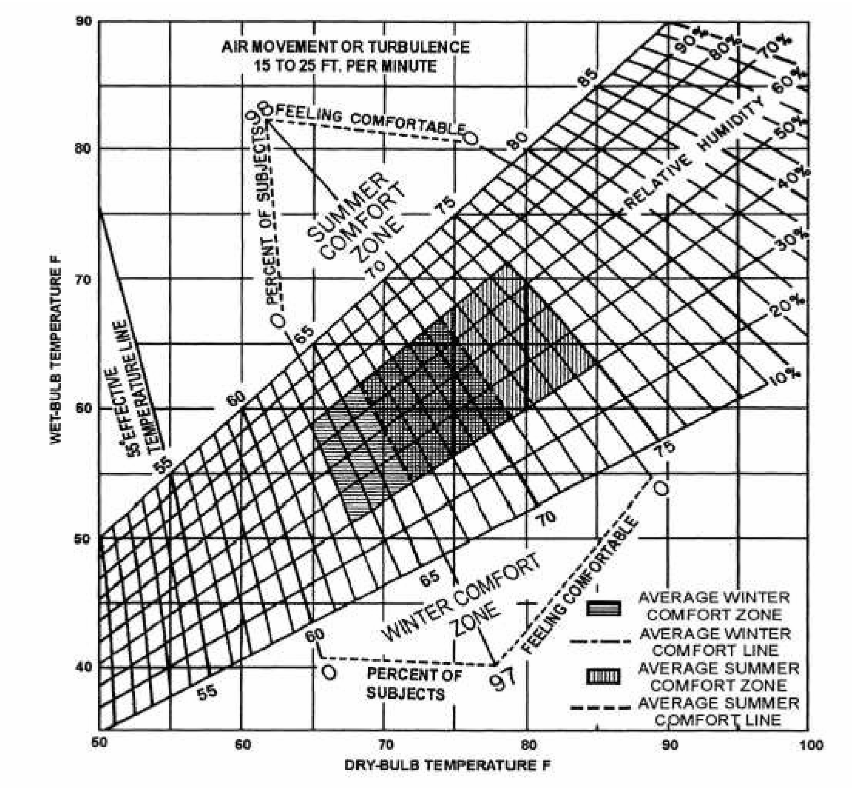


Figure 4. The Comfort Zone shown on a psychrometric chart (ASH&VE)

In concluding this section it is worth noting that building services design was, and is not *only* a matter of using a knowledge of thermodynamics. No less important is what to use it for, and many early air-conditioning systems were poorly conceived as building systems. In March 1925 one exasperated engineer got his very practical advice published in the Heating & Ventilation Magazine (p.45).

Don'ts for Theatre Ventilation

1. Don't use the mushroom system of supply for cold air.
2. Don't pass all air through the cooler.
3. Don't omit complete mechanical exhaust with refrigerating systems.
4. Don't omit automatic temperature control with refrigerating systems.

5. Don’t supply cold air at low points and expect to pull it up with exhaust .
6. Don’t supply warm air at high points and expect to pull it down with exhaust.
7. Don’t expect to pull air any place. You can push but you cannot pull.
8. Don’t conceive of a theatre as a tight box. It never is.
9. Don’t introduce air into a theatre auditorium from the rear unless you know exactly where it is going and can accurately control its temperature and velocity.
10. Don’t expect a thermostat on the main floor to maintain conditions of comfort in the balcony, or vice versa.
11. Don’t supply air to the main floor and balcony, or to the main floor and dressing rooms with the same fan.
12. Don’t expect air currents to follow trained arrows on plans, unless you are sure the arrows are thoroughly and properly trained.
13. Don’t expect a Rolls-Royce ventilation system at the cost of a Ford.

From the 1930s progress in many branches of building engineering was accelerated through the use of scale models. When a phenomenon is studied at more than one scale it is soon possible to establish the effect of scale on different parameters and this guides the experimenter towards a full scientific understanding of the phenomenon. Models, of course, were also cheaper to build and to alter for different tests than a full-size prototype. By the use of non-dimensional constants it is possible to scale up measurements made on the model to predict full-size behaviour (Cowan et al 1968). One such set of tests was undertaken on models to investigate the flow of air through ventilation windows when heated in a fire (Thomas 1992). The results enabled the performance in a full-scale fire to be predicted with great accuracy.

DAYLIGHT

Drivers

Since ancient times it has been the right of a building owner that an adequate quantity of daylight should enter the rooms of his building and was especially important in the days before good artificial light could be provided by gas (from the 1810s) or electricity (from the 1880s). This right to light had been established to prevent new buildings being constructed that would reduce the daylight entering the windows of an existing building. As towns and cities grew, so the pressure from property developers to build new and larger buildings next to older ones and it was in the courts that possible infringements of the right to light were tested. The need to resolve such disputes was thus a primary driver for developing means of measuring the quantity of daylight entering a room. The earliest requirement that the designers of a new building should consider daylight was thus, ironically, to establish the levels of daylight in existing, adjacent buildings rather than the new one.

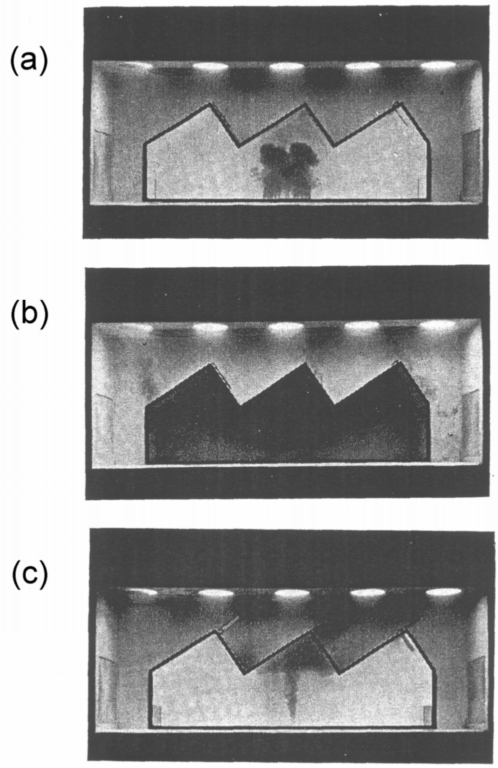


Figure 5. Quantitative model tests for predicting removal smoke build-up (a) start of fire; (b) smoke build-up without ventilation; (c) reduction of build-up with roof-light ventilation (Building Research Establishment)

It was in the design of new schools that the provision of daylight first became a significant issue for their designers. From the 1890s a number of scientists in Austria, Germany, Britain and the USA began to suspect a link between eyesight defects in schoolchildren and lighting levels. Although a direct cause-and-effect was not established, the issue was politically highly emotive and by 1920 many countries had set minimum lighting levels for different types of room that had to be achieved using either daylight or artificial light.

Design in pre-scientific times

Even today there is no absolute measure of the quantity light needed in a room because it depends very much on the human activity being undertaken in the room. Someone threading an occasional needle in a living room can do so in much lower light levels than a factory worker required to thread needles all day. The accuracy needed to perform a task is also significant – a watchmaker needs better lighting than a shoemaker. The desirable level of lighting in rooms also varies with the individuals involved – children can read in much lower lighting levels than older people and people with perfect vision need less light than people who need glasses. Finally, the perceived intensity of lighting does not vary linearly with the quantity of light entering the eye – the relationship is logarithmic and the smallest change of illumination that the eye can detect is a doubling of the intensity.

Over many centuries the lighting levels considered adequate for different rooms and activities had been established according to what people found comfortable or, at least, bearable. There developed various simple guidelines relating the ratios of the area of window in a room to the wall area and to the height and depth of the room.

The development of rules for the design of schools became more sophisticated during the second half of the nineteenth century. A design rule dating from 1866 suggested that the window area in each room should be at least one-fifth of the floor area, though this was seldom complied with. A later French design rule proposed that some sky should be visible from every pupil's seat and that schools should be separated from adjacent buildings by a distance of at least twice their height. A rule from the French Education Department in 1882 stated that a piece of sky equal to 30 centimetres from the top of the window should be visible from every seat. At about the same time in Germany the idea of the "Offnungswinkel" or 'opening angle' was conceived as a measure of the angle of sky visible from a pupil's desk between the top of the window and the top of the adjacent building; a minimum of 4° was recommended (Kerr 1913)

The scientific concepts

The earliest measure of lighting levels was in terms of the illumination provided by candles or, rather, the illumination provided by a certain light source *relative to* a standard (called, in Britain, the "British Standard Candle"). Methods developed in the late eighteenth century for comparing the strengths of light sources involved moving the unknown light source to a position such that the intensity of its illumination of a screen matched that of the known (standard) source. Since British Standard Candles were found to vary by more than 20%, this was not a very reliable method. Standard sources of illumination using gas flames that were accurate to within 3-4% were developed in the 1820s.

Such methods did not, however, measure the quantity of light falling on a work surface in a room which depends not only on the distance between an artificial light and the surface, and also the light reaching the work surface after reflection off walls and the ceiling. There might also be light arriving from several light sources at different places in a room and there would be a considerable additional contribution from any daylight entering the room, arriving at the work surface, both directly and indirectly after reflections.

The first attempts at measuring the light falling on a work surface were in Germany in the 1880s, using photographic paper that was exposed for a standard time (e.g. one hour). The first selenium photometers that created an electrical output dependent on the incident light were developed in the 1890s and soon used for assessing daylight in school rooms in France and all the German-speaking countries. They were not used in Britain until the 1930s.

The idea of measuring the spherical angle of sky that was visible from a point in a room was also conceived in the 1880s in Germany. By the use of this concept the level of daylight falling on a work surface in a room could be calculated from drawings of the room and its windows; no measurements of light were necessary. By the end of the 1880s the calculation had been developed to include the additional effect of light reflected from the internal surfaces of the room. In Britain a similar approach was being followed by the physicist A. P. Trotter (Trotter 1892). He later coined the phrase 'daylight factor', still in use today, defining it as a means of assessing what proportion of the maximum available daylight reaches the interior of a room. For a school room this would typically be 2-3% and for intricate handwork, from 3-5% or even higher (Hawkes 1970).

Scientific design methods

Calculating the daylight factor from drawings was a tedious process involving three dimensional geometry and the analysis of light reflected off walls and ceilings, and could not be done quickly. To help the designer, scientists at the Building Research Station developed a number of computational design aids to help the busy designer. These included bespoke protractors, nomograms (Fig 3) and a dedicated slide rule.

Since the daylight factor approach involves the intensity of illumination relative to a standard (full daylight), it was not a large step to make daylighting studies using scale models of school rooms, including walls and furniture with the appropriate reflectivity. Using a 'relative photometer, the light intensity was studied and could readily be scaled up to full size. It was inexpensive to make adjustments to the model to rectify any problems that the tests exposed (Ruzicka 1908).

Another design aid to come out of the Building Research Station in the 1930s was the *heliodon* (Dufton & Beckett 1931). This simple and ingenious device allows the designer to study the effects of direct sunlight on a building – both the shadows cast by adjacent buildings and by the sunlight entering a window – at any time of day and at any position on the earth's surface. The designer can quickly see the effects and calculate the periods of the day when shadows might be a nuisance and hence whether and how they should be avoided – calculations in three dimensional geometry that would otherwise have been far too tedious to undertake from first principles in the pre-computer age.

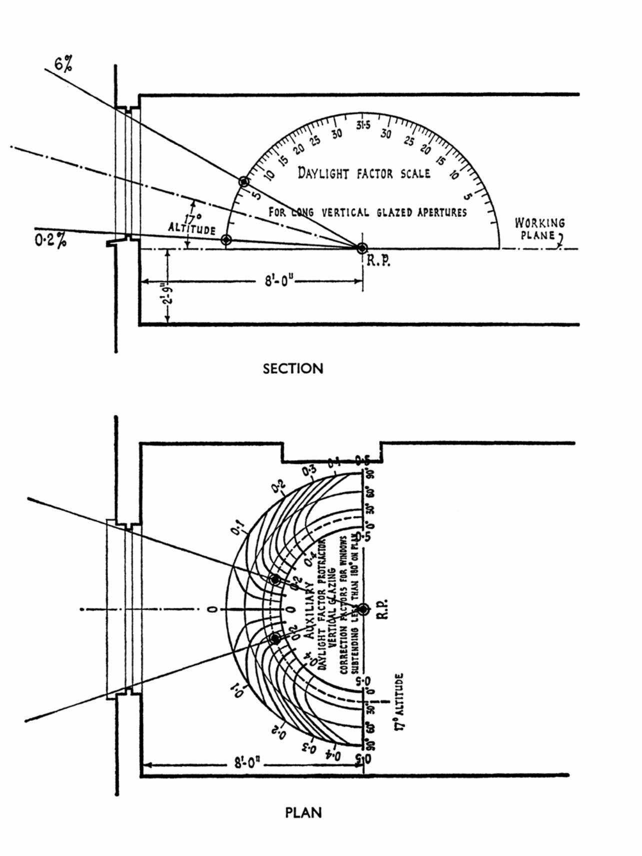


Figure 6. Daylight factor protractor (Building Research Station)

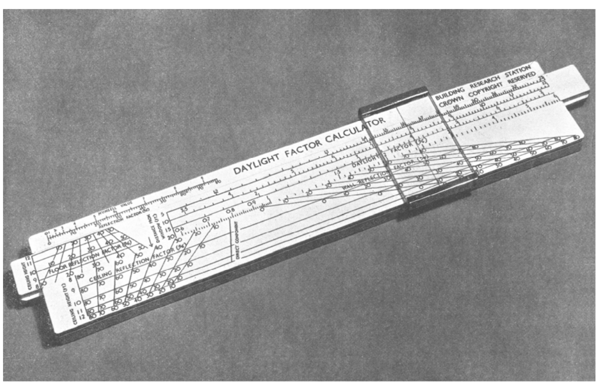


Figure 7. Daylight factor slide rule (Building Research Station)

Figure 8. The original heliodon devised in 1931 (Building Research Station)

ROOM ACOUSTICS

Drivers

As in the ancient world of building described by Vitruvius, it was the intelligibility of speech that attracted the attention of seventeenth and eighteenth century building designers to the acoustic performance of building interiors. This was especially important in two types of enclosed space – the debating chambers used by politicians and theatres. During the eighteenth century the importance of room acoustics was further heightened with the growing popularity, in elite circles at least, of chamber music and improved musical instruments such as the harpsichord and fortepiano that used ingenious mechanisms and large sounding boards to produce plucked and percussive notes with unprecedented speed and at much greater volumes than earlier instruments such as the lute, harp and clavichord. When played in a room with a very live acoustic, the individual notes became indistinguishable and the objectives of the instrument makers and musicians were ruined.

Design in pre-scientific times

It was well-understood that the size of a room and the reflectivity of the walls, floor and ceiling affected the intelligibility of speech and music, and that two different effects were at work. One was the loudness or intensity of the sound that diminished with distance and according to the amount of sound absorbed by the room's surfaces and contents. The second was the increasing confusion of words or music caused by strong reflections from the room's surfaces.

This understanding of acoustics led building designers to use a number of pragmatic rules that helped them achieve acceptable room acoustics. Three different types of surface could be used – stone or plaster would enhance reflections, woven fabric such as tapestries and curtains would absorb sound, and timber panelling was intermediate between the two. Based on the acoustic performance of existing rooms, a designer could choose what he hoped would be a suitable combination of the three types of surface. The other design factor was the distance between speaker or instrument, and the directness of the sound path. Theatre designers tried to ensure that that the entire audience could see the actors, not only for theatrical effect, but so that at least some of the sound could travel directly from speaker to listener. The other consideration was the distance between the stage and the listener. It was generally agreed that an actor speaking in a normal voice could be understood clearly up to a distance of about fifty feet, and with difficulty up to about eighty feet. The result of these basic rules was the development of the familiar raked seating and tiers of balconies in theatres and dedicated concert halls.

Design rules for theatre acoustics were not very reliable in the eighteenth century and there were many acoustic disasters. In his autobiography of 1740, the actor and playwright Colley Cibber wrote of Vanbrugh's Queen's Theatre in London, built in 1704-05, that all its architectural elegance was of no avail:

> . . . when scarce one word in ten could be distinctly heard . . . The extraordinary and superfluous space occasioned such an undulation from the voice of every actor that generally what they said sounded like the gabbling of so many people in the lofty aisles in a cathedral … [and] the articulate[d] sounds of a speaking voice were drowned by the hollow reverberations of one word upon another.'
>
> (Leacroft 1973, 102)

In the 1780s the English theatre designer George Saunders (c.1762-1839) began to undertake tests of audibility in auditoria. For example it was established that the audience should not be further than 70 feet from the actors. Physicists soon began to take an interested and the first comprehensive book on acoustics was published in 1802 (Die Akustik by Chladni.). He advised that "rooms will be favourable to the transmission of sound":

1. When arranged to facilitate its natural progress;
2. When its intensity is augmented by resonance or simultaneous reflection, so that the reaction is undistinguishable from the primitive sound;
3. When not too lofty or too vaulted;
4. When there is not a too extensive for the sound to strike against at once
5. When the seats are successively elevated.

He also observed that:

> - when the enclosed space does not exceed 65 feet, any form may be adopted for a room;
>
> - that elliptical, circular, and semi-circular plans produce prolonged reverberations;
>
> - parabolic plans and ceilings are the best for distinct hearing.
>
> And that for concert rooms, square and polygonal plans should have pyramidal ceilings, and circular plans domed ones, and the orchestra be placed on high, in the centre, to produce the best effect and avoid echo."

Saunders' and Chladni's design rules were widely quoted and used throughout the nineteenth century.

The scientific concepts

The basic scientific concept of room acoustics – the reverberation time – was invented in the first decade of the twentieth century by the American physicist Wallace Clement Sabine (1868-1919). In 1895 he was called upon to advise on how to improve the acoustics of a number of lecture theatres at his own university, Harvard (Sabine 1925). In that pre-electric age, and working at night to avoid extraneous sounds, he used an organ pipe to generate a single pure note. He then terminated the note and timed the decay of the sound to the point at which it was inaudible. He repeated this for different notes and found that the reverberation time varied according to the note. He then repeated the measurements having changed the absorptivity of parts of the walls of the rooms, the audience seating and even the floor. Sabine later studied rooms of different sizes and established the reverberation times that were most suitable for good intelligibility of speech and for music. Furthermore he discovered the relationship between reverberation time and the volume of the room and the effect of the absorptivity of the various surfaces of a room.

Scientific design methods

Having started with the need to find a remedy for an acoustic problem Sabine soon turned his understanding to the design of new rooms, in particular some concert halls, and predicted their reverberation times before they were built (Sabine 1925). He later turned his attention to creating a near-uniform acoustic experience for every member of the audience. To help him in these studies he used a newly-perfected method of photography to show sound waves passing through air in two-dimensional scale models of auditoria. He thus showed in plan and section, how sound waves were reflected and broken up as they emanated from the stage into the auditorium.

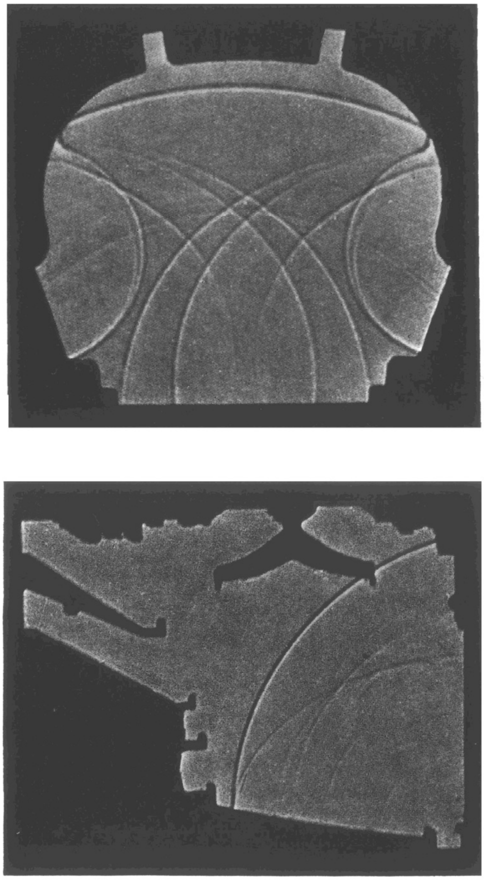
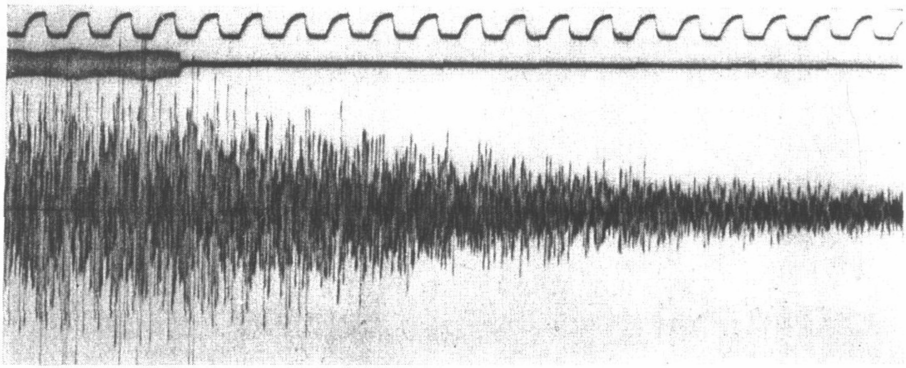


Figure 9. Use of models to investigate propagation of sound a theatre (Sabine 1925)

Sabine’s model testing was qualitative rather than quantitative. Scale models were first used to analyse the acoustic performance of auditoria by the German physicist Friedrich Spandoek in the early 1930s (Spandoek 1934). Using dimensional analysis to find suitable dimensionless constants, he showed that the acoustic behaviour of a room varies inversely with the model scale – for a one-fifth scale model, the sound frequencies used for testing need to be five times higher than normal frequencies. He also recognised the need to ensure the temperature, pressure and density of the air in the model room were identical to a real room, since these affect the speed of different frequencies of sound differently. Spandoek studied the effect on both the decay of sound and its distribution throughout the auditorium of raked seating (better) and a semi-circular wall behind the stage (worse). Using a microphone he displayed the decay of sound in the model auditorium on the screen of an oscilloscope, and recorded the results in a photograph.



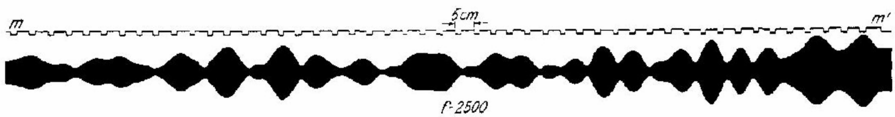


Figure 10. Above: decay of sound in a room photographed from an ossicoloscope;
Below: Variation in sound intensity from font to back of a lecture theatre (Spandoek 1934)

The use of models in acoustic design was greatly developed by in the 1960s by the Danish acoustician Vilhelm Jordan (1909-1982). He was able to use much better equipment than had been available to Spandoek – small microphones and loudspeakers as well as high-quality tape recorders to analyse the results of the acoustic tests. Probably his most famous commission was the Sydney Opera House (Jordan 1980). Using 1:10 scale models of the two auditoria of unprecedented shapes, he was able to create the acoustic that they needed. They demonstrated the benefits of introducing flat side walls to the auditoria to provide lateral reflections, and reflective interiors to the boxes. They also showed that the ceiling originally proposed for the main auditorium, consisting of large catenaries hung longitudinally from the external shell, left the orchestra area suffering from a deficiency of early reflected sound. Many different shapes and positions of reflectors suspended above the orchestra were studied throughout the design stages.

It is worth ending this section by observing that the science of acoustics is still in its infancy and there is still a long way to go for scientists to find suitable parameters that correspond to the terms that musicians and audiences use to describe the acoustic quality of concert halls using words such as ‘warmth’, ‘intimacy’, resonance’ and ‘fullness of tone’.

CONCLUDING REMARKS

Among the various branches of building services engineering we find similarities in how modern design methods developed from their ancestors in pre-scientific times:

- Generally engineers have favoured geometric calculation methods over algebraic/ numerical ones (unlike scientists).

- Calculation methods and tools for engineers were developed mainly in France and Germany in the eighteenth and nineteenth centuries. Before the twentieth century the numerical skills of the 'average' engineer in Britain and the USA lagged well behind that of their continental European colleagues.

- Empirical design rules were developed for all aspects of building design. Based on experience, some were quantitative and some qualitative.

- Different building types have been at the forefront of developments in different branches of building engineering. Generally developments occurred first in buildings for which there were strong commercial drivers.

- The first step toward scientific design methods was the use of relative measures which allowed comparison of a new design with existing ones. Absolute measures of came only when the science underlying an engineering system was understood.

- The first step towards developing an understanding of the science of an engineering system was usually stimulated by the need to solve a problem with existing buildings (e.g. the need to heat textile mills to prevent wool and cotton threads from snapping; disease resulting from poor ventilation; the need to cool buildings that were uncomfortable in hot climates; the effects of poor daylighting on children's eyesight; inaudible speakers in rooms with acoustic problems).

- Scale models were used as design tools at some stage during the development of most scientific design methods. Scientific understanding often arose from establishing the precise relationship between the performance of a scale model and the full-size version.

Figure 11. Vilhelm Jordan in his acoustic model of the Sydney Opera House (Jordan Akustik)

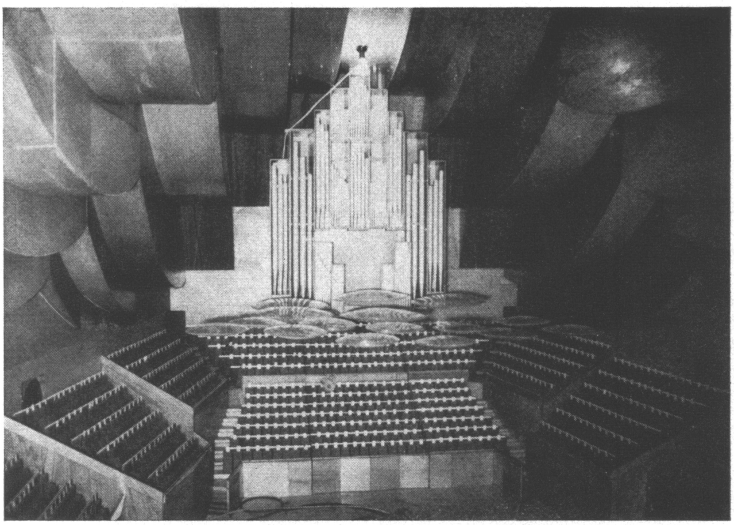


Figure 12 a

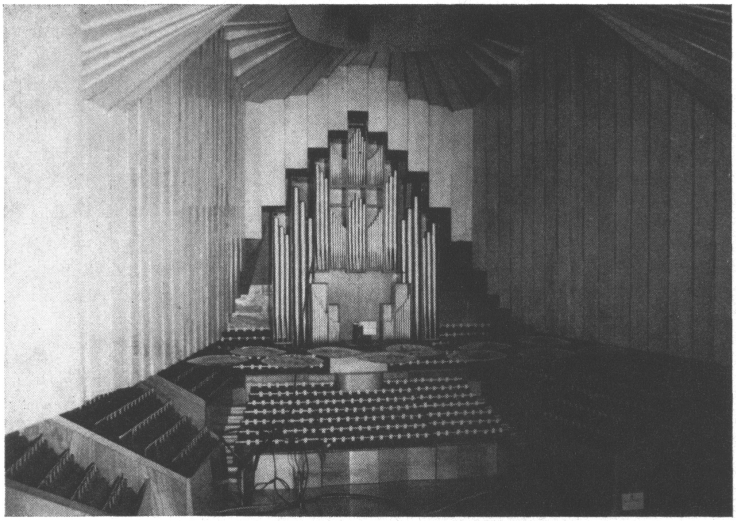


Figure 12. Two arrangements of the interior of Sydney Opera House investigated by Jordan (Jordan Akustik)

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