# The role of wood in healthy buildings

## 1: Introduction

The impact our buildings have on how we work, heal, learn and rest is highly significant, whether it is productivity in offices, patient recovery, student performance, or our own comfort at home – all are influenced by the indoor environment and the design, products and systems used to create and furnish our buildings.

But what do we mean by the term *healthy buildings*? Hal Levin defined a healthy building as 'one that adversely affects neither the health of its occupants nor the larger environment'[1]. It is a complex field, with claims of exciting improvements to productivity based on changes to interiors in workplaces, but studying people and measuring people's perceptions can be qualitative and study-specific. The idea of a solution that fits all is misleading, but there are principles in common that work towards improvements in indoor environments and the creation of healthier buildings. Empirical studies have documented that both active and passive experiences of nature may be beneficial for human health and wellbeing. The use of natural materials such as wood is expected to improve the user experience and provide connection to nature.

**Figure 1** Sunbeams Music Centre utilises several timber species in order to provide a warm interior that is predominantly naturally ventilated and lit

Photograph: © Simon Kennedy

The theme of healthy buildings is woven into environmental assessment, circular economy, design economics, project budgets and material selection. Modern construction has seen a rise in the use of natural materials, including timber. Cost-effective, efficient, lightweight and environmentally responsible features are evident, not least by the rise of timber in medium to tall buildings, and new features are emerging such as softer aesthetic and comfort choices. This briefing document looks at the increasing evidence base that underpins these emerging features, expanding and supporting the use of timber in construction, especially in interiors, where humans will interact with materials either directly by visual or haptic senses, or indirectly through smell, air quality, humidity buffering and thermal comfort.

## 2: What makes a building healthy?

Our personal health and wellbeing are conventionally framed around our physical health (the absence of disease and optimal function of the body), mental health (how we think, feel and cope with daily life) and social health (how we react to other individuals and groups and how they react to us).

Our interactions with our surroundings and the influence our surroundings have on our health and wellbeing are subject to much debate, analysis and discussion in the construction industry. Fundamentally, a building should go beyond eliminating negative impacts on our health to be a building that has positive impacts on our physical health (through layout, use of stairs, air purification), mental health (function, places to rest and restore, aesthetic, stimulation) and social health (places to meet, promote collaboration, learn). There is much to learn in the field of healthy building science, which has a diverse scope – from the impacts of poor buildings on us to the potential for the use of wood in interiors to have a positive impact on us.

### 2.1. Types of healthy building

Healthy buildings should support the physical, psychological and social health and wellbeing of people, recognising the fact that buildings – how they are designed, built and operated –

are key promoters of health and wellbeing. Healthy building frameworks typically consider air, water, active design, lighting, acoustics, materials and comfort to deliver healthy buildings. The functional outcomes will depend on building typology.

For example, the UK Government[2] indicates that **healthcare buildings** should provide a therapeutic environment in which the overall design and detailing contributes to the process of healing and reduces the risk of healthcare-associated infections. The Healthy Pupils Capital Fund[3] provides funds for projects that promote physical and mental health of young people by increasing access to facilities that allow physical activity, healthy eating, mental health and wellbeing, and the treatment of medical conditions. This includes refurbishment or building of facilities and spaces, and recognition of the fundamental role buildings have in positive outcomes at school.

**Schools and education buildings** should promote learning. Poor school design can cause students to switch off and may even impact on their mental health. Studies such as those by the US Green Building Council (USGBC) and the McGraw Hill Foundation[4] document the state of school buildings and their impacts; evidence shows that good-quality aural environments (eliminating background noise), natural light (to maintain alertness), thermal comfort controls, ventilation rates (fresh, clean air) and stimulating environments all contribute to healthy schools.

**Office workplaces** aim to promote task achievement and performance, as well as collaboration and a range of business success measures. The focus of much recent attention, including the ongoing BRE Biophilic Office Project[5], are the business benefits of collaboration, communication, quality and productivity. These factors, as well as keeping talent in the business, can reduce absenteeism and days lost to sickness.

**Social and private housing** should promote a healthier lifestyle. This is more challenging against the backdrop of the variety of personal habits, furnishing tastes and priorities. However, a new or refurbished home could provide a positive interior focusing on primary areas where families socialise, low to no volatile organic compound (VOC) product solutions, and a connection to outdoor shared spaces with neighbours, among other features.

## 2.2. Important considerations

Healthy buildings are prominent in construction discussions, though the interpretation is varied and sometimes focuses on one topic, such as indoor air quality. In part the prominence has been driven by consumer awareness of personal health and the impacts from actions and the surroundings, but also from threads of philosophical movements to build better places for people.

We record the impact of unhealthy buildings and the problems we encounter in buildings. Damp, for example, is known to have significant impacts on building occupants; BRE showed that poor-quality homes in England cost the NHS £1.4bn, with £16m linked to damp and mould growth[6]. Equally, and overlapping with damp, indoor air quality is a common issue, with emissions from products and occupants, plus the building ventilation rates, involved. Poor provision for ventilation may be exacerbated by design to reduce energy consumption and/or by occupants excluding noise and pollution. In summer this can increase the risk of overheating.

Indoor air quality is complex, and an approach focusing on high $CO_2$ levels is often encountered as these are easy to detect and are known to have a negative impact. The threshold set in the Chartered Institution of Building Services Engineers (CIBSE) workplace standards when considering healthy buildings is 1,000ppm[7]. In all teaching and learning spaces the average concentration of $CO_2$ should not exceed 1,500ppm[8]. There is a need to be specific about pollutants of concern, and what might be defined as 'healthy' air. While it is easier to detect substances such as $CO_2$ or total VOCs, they are not always directly linked to specific health effects.

The global architectural firm HOK's workplace review[9] highlighted ten fundamental design elements that can positively impact the workplace environment. Fundamental components that influence occupant health and wellbeing, and to an extent the functional purpose of a building, are given in *Table 1*. Those highlighted in blue provide the main focus of this publication.

**Table 1** Influences on building occupant health and wellbeing

| Building environment | Timber in healthy buildings | Occupant |
|---|---|---|
| Indoor air quality | Indirect contact with nature | Design, layout and ergonomics |
| Acoustic quality | Visual variety | Choice |
| Daylight and lighting | Haptic qualities | Engagement |
| Hygrothermal mass | Colour | Comfort |
| Thermal comfort | Aesthetic | Occupancy level |
| Views of nature | | |

Other important aspects that are covered briefly below include damp, design and biophilia.

### *2.2.1. Damp and mould*

Operation and maintenance of a building has a major impact on whether it might be considered a healthy building or not. There has long been attention drawn to the problem of moisture and damp in homes and their impact on occupant health. The UK Centre for Moisture in Buildings has reviewed the evidence linking moisture in buildings to ill-health[10]. Numerous studies suggest strong relationships between mould and a range of health problems – mainly but not exclusively respiratory. House dust mites, which are more prevalent in damper (and warmer) conditions, are also known to cause and exacerbate asthma. The fundamental issues of damp may be due to poor design and operation, and are frequently due to poor maintenance and dereliction.

### *2.2.2. Design and ergonomics*

Burnard and Kutnar[11] at the InnoRenew Centre of Excellence in Slovenia lead the field in Europe presenting restorative environmental design (RED) and particularly how wood acts as a material complement. The goals of RED are to reduce environmental impacts of new buildings, and to ensure buildings provide health benefits to the occupants. RED has been discussed as being the next evolution of 'green' sustainable design as it combines the goals of environmental sustainability with providing wellness benefits to occupants, while also reinforcing the human–nature connection[12]. Kutnar[13] combined RED with ergonomic interventions in buildings and products to create restorative environmental and ergonomic design (REED). They suggest that wood is an ideal material for REED as it satisfies both general tenets of the design paradigm: sustainability and a connection to nature. Fundamental to healthy buildings is the design and ergonomics of the spaces within them for the functions required.

### *2.2.3. Biophilia and nature therapy*

Biophilia acknowledges our genetic connection to nature[14]. The health and wellbeing benefits for building occupants and the promotion of the connection to nature can be achieved by implementing biophilic design[15]. Terrapin Bright Green pioneered biophilic design with their 14 patterns of biophilic design[16], which are deployed internationally. These projects provide a growing body of evidence demonstrating that connection to nature, biophilic design and wood are associated with improved physical and mental wellbeing.

There has long been an understanding and appreciation of the healing power of forests and woodlands. Different feelings of comfort reported between forest and city environments looking at the physiological influences of such environments reported that cerebral activity and salivary cortisol levels reflect a relaxing influence for panellists in a forest environment compared to a city[17]. This supports the ancient practice of shinrin-yoku (forest bathing) prescribed by Japanese medical practitioners as part of the treatment for various conditions, including mental health conditions.

A review conducted by Song et al. covers the effects of nature therapy on activities of the central nervous system, autonomic nervous system, endocrine system and immune system[18]. In recent years, scientific evidence supporting the physiological effects of relaxation caused by natural stimuli has accumulated. The authors believe that nature therapy will play an increasingly important role in preventive medicine in the future as the therapeutic effects of natural stimulation suggest a simple, accessible and cost-effective method to improve the quality of life and health of people.

### *2.2.4. Haptic qualities of wood*

The term *haptic* is used to refer to interactions involving touch. Work in the Wood2New project confirmed haptic properties, moisture buffering effect and the hygroscopic capacity of various wood species, as well as variations in VOC emissions due to changes in moisture content. Colour, surface structure and surface temperature are the main properties that impact human perception.

Holzforschung Austria ran a study in which blindfolded persons judged the haptic perception of different wood and non-wood materials at different temperatures[19]. Using a bare hand, they judged the perception of temperature, general comfort and sweating, as well as whether the material in question was wood or not. With bare feet, the participants in the study judged the perception of temperature only.

Haptics and tactile properties influence decisions by choosing products and materials consciously and unconsciously. The touch of uncoated (if not too rough) wood was often felt to be comfortable, and coatings significantly influence the sensation of wooden materials. With oil surface treatments the haptic character of wood was retained very well, because oil does not usually form a layer on the surface. Humans can judge very well a material type by touching a surface, where the temperature sensation is an important factor; without touching, however, it is often very difficult to differentiate between wood and imitation, especially when viewed from a distance.

### *2.2.5. Hygrothermal mass*

Temperature and moisture are central characteristics of interior spaces and research suggests that these can be affected by the choice of surface materials. Part of the Wood2New project studied wood's propensity to interact with moisture[20], which can be put to good effect in helping to mediate the interior environment of buildings. As the humidity level rises, wood adsorbs moisture from the surrounding air and, when the humidity drops, the stored moisture is released back into the environment. Associated with adsorption is a release of heat, which can raise the surface temperature of wood; conversely, heat is required during desorption. These processes combined with the other thermal properties of wood give rise to the concept of 'hygrothermal mass', which may have the potential to improve the energy efficiency of buildings. These attributes are gradually being recognised.

Gaia Architects looked at a range of measures currently not included in conventional energy design for Passivhaus[21]. One of the most important measures is the utilisation of the hygrothermal properties of wood to stabilise the moisture level in indoor air, and to prevent moisture loads on surfaces and structures. Nore described the concept of hygrothermal mass as wood in an environment seeking equilibrium with the environmental conditions[22]. Thermal mass is about the mass of the building as the energy reservoir, while hygrothermal mass is about moisture as the energy reservoir in the building. Wood is hygroscopic and the transport and storage of moisture, then the emission of sorption heat, can fit with the diurnal climate variations experienced in buildings. A case study in Kiwi Fjeldset, a supermarket in Norway, in 2016 retrofitted wood into the ceiling area to buffer moisture fluctuations, which resulted in reduced operational use of the mechanical ventilation with heat recovery units.

## 2.3. Healthy materials: the role of wood

Timber is a highly versatile material that can feature in the main structural components of a building, the insulation, the linings, floor cassettes, floor finishes, furniture, cladding and fit-out. Materials make the building and, with the building operation and management, create many of the impacts (potentially positive and negative) on occupants related to internal conditions.

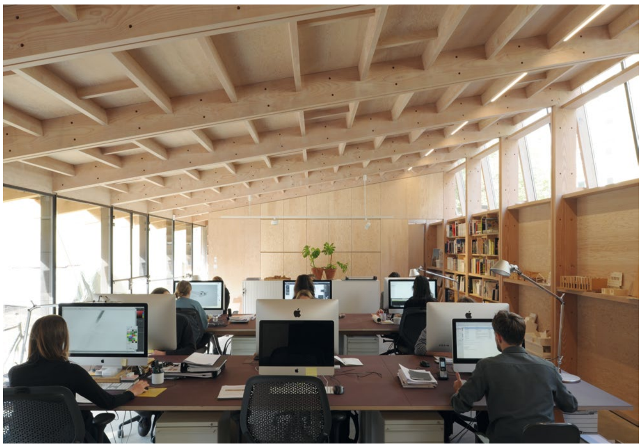


**Figure 2** The Feilden Fowles Studio was designed to demonstrate a rational model for contemporary work and education spaces
Photograph: © David Grandorge

Research has found that the visual presence of wood indoors can significantly reduce stress levels among building occupants. Stress increases blood pressure and heart rate, and weakens the immune system, as well as causing irritability and a lack of focus. Those factors can lead to a decline in general health and task performance among occupants. According to Fell, and others, the multiple physiological and psychological health benefits identified for wooden interiors include[23]:

- reduced blood pressure, heart rate and stress levels
- improved attention and focus
- improved emotional state and level of self-expression
- greater creativity
- quicker recovery
- reduced pain perception.

Wood is associated with warmth – it is a natural insulator, as well as having warm colour tones. Buildings that use wood in structural and finish applications have the potential to yield high levels of thermal comfort and mitigate sound and have improved air quality through humidity moderation. The evidence is looked at in detail in *Section 4* of this briefing document.

## 2.4. Materials and indoor air quality

The indoor air environment is complex; considerations include humidity, temperature and sources of pollutants in the space, as well as air movement and ventilation rates. Pollutants can come from occupants, outdoor air and from products in the building. For pollutants associated with the materials in construction products, furnishings and fit-out, the nature and source of any chemical, its chemical state within a material or product, its ability to pass into the indoor air, its effect on humans when in the air, and the ability to remove it from the air by ventilation are all important considerations. As individuals, we are all different, and consideration of indoor air quality must include the personal habits and preferences of occupants, which strongly influence the indoor environments encountered in our homes and workplaces.

The ground-breaking Royal College of Physicians report, *Every breath we take*, considered air pollution in detail and its impacts on us, gathering literature and evidence around air quality, with the pollution sources reviewed by a working group of experts[24]. Among the 18 listed groups of pollutants emitted from indoor sources, those of significance for timber in healthy buildings are (1) formaldehyde from composite wood furniture and fittings; and (2) insecticides from timber treatment and pesticide sprays, which are assumed to be remedial timber treatments. The report notes that asthmagens that might be of relevance to wood products include di-isocyanates, wood dust and cleaning agents.

Often no single authority or profession has overall responsibility for indoor air quality. *Every breath we take* noted that positive examples of legislative instruments include the Building Regulations, which exert some control over ventilation requirements and radon gas ingress, as well as the highly successful ban on smoking in public places.

The World Health Organization classifies organic pollutants according to three types, based on their boiling points (*Table 2*).[25] They are often summed and reported as total volatile organic compounds (TVOC), a value for which may appear in certification schemes as a threshold limit – e.g. in BREEAM the TVOC threshold is 300µg/m$^3$.

**Table 2** World Health Organization classification of VOCs

| Type | Boiling point (°C) |
|---|---|
| Very VOC | <0 to 50–100 |
| VOC | 50–100 to 240–260 |
| Semi-VOC | 240–260 to 380–400 |

Individual VOCs have different impacts on human health, from none, to serious skin, eye and throat irritations. Safe exposure limits to individual VOCs may be defined, but the combinations of multiple VOCs and long-term exposure impacts are less well understood. This also includes particulates such as PM2.5 and PM10, which are frequently associated with outdoor air pollution from traffic and the burning of fossil fuels. These tiny particulates are especially damaging and can pass from outdoor air to indoor air. Particulates are also generated indoors from cooking and open fires.

The actual concentration of pollutants (formaldehyde, VOCs and particulates) in indoor air is influenced by the outdoor air quality, occupant behaviour (smoking, cooking, cleaning, personal hygiene, pets), emissions from the building fabric and fit-out and emissions from the building contents. The concentration is reduced by the ventilation rate in the building and the adsorption to surfaces in the building. Much of this, especially in private homes, cannot be controlled. However, if we consider materials for construction products, we can take control of the emissions that will come from the materials selected for the building fabric and fit-out. For timber and wood-based products this may include the structure, insulation, flooring, wall linings, attic spaces, floor cassettes, wood panelling, floor finishes, etc. It would also include furniture and kitchen and bathroom units, which are not covered in this briefing.

## 2.5. Emissions from wood

All materials emit compounds to air as the volatilisation of chemicals contained within the material or as secondary or tertiary breakdown products as the material ages. Principal concerns for construction products focus on VOCs – a group of chemical substances that volatilise (see *Table 2*). When measuring VOCs in indoor air and ascribing it as indoor air quality, it is fundamental to understand (1) that a measurement is a snapshot for that building on that day and under those conditions of ventilation; and (2) that the compounds detected will come from the outdoor air, the building and interior fit-out, and the occupants and their behaviours.

Wood and wood products are no different from other construction materials in that they emit VOCs post-manufacture. The emission of VOCs from wood and wood products is important in evaluating the impact on the indoor environment from different materials. The results from analyses of emissions by Risholm-Sundman et al. from nine different wood species found the main emissions to be terpenes from softwood and acetic acid from hardwood[26].

Soto-Garcia et al. investigated the VOCs that were off-gassed from stored wood pellets[27]. This is not directly relevant to a wood product in a building as wood pellets have a surface area many tens of thousands of times greater from which to emit compounds than a solid wood board, but the study showed the main VOCs produced are due to wood oxidation – methanol, pentane, pentanal and hexanal. Higher concentrations, but lower emission rates, were found from softwood followed by blended pellets and then hardwood pellets.

The impact of wood use in a hospital environment has been assessed[28]. VOC air concentration was measured in hospital rooms in a newly built hospital in Norway. No significant differences in VOC air concentrations were found between the room designs with or without wooden panels. The use of wooden wall panels in hospital rooms had no effect on the amount of VOCs in the indoor environment.

Zylkowski and Frihart recorded $\alpha$-pinenes as one of those VOCs that are part of the naturally present compounds in softwoods like pine, which give it the familiar pine smell[29]. $\alpha$-pinene has known beneficial effects and is present in the oils of many species of coniferous trees, most notably pine, and is known for its diverse biological properties, including antimicrobial, anti-inflammatory, antiproliferative and antioxidant properties. Türkez and Aydın investigated the genetic, oxidative, and cytotoxic effects of $\alpha$-pinene in cultured human blood cells[30]. They found that $\alpha$-pinene could be a significant source of natural antioxidant compounds that have beneficial health effects.

Naturally occurring VOCs are being considered in some depth regarding their positive qualities and impacts on humans. For example, Song et al. reported on the effects on human physiology and psychology of VOCs emitted by trees[31]. The main volatile compounds of Shantung maple (*Acer truncatum*) included hexenols and acetic acid hexyl ester, and the main volatile compounds from Himalayan cedar (*Cedrus deodara*) included $\beta$-myrcene, D-limonene and pinene. After sniffing volatile compounds from *Himalayan cedar*, blood oxygen saturation increased and systolic blood pressure, diastolic blood pressure and heart rate all reduced. Nearly 50% of respondents reported liking the smell of Shantung maple and Himalayan cedar, and associated the smell with a natural feeling.

A material emission database has been developed for 48 building materials, based on ASTM test methods[32]. The database consists of model coefficients for the five or six most abundant VOCs emitted from each building material. The authors suggest that, as the database is linked to a single-zone indoor air quality simulation programme, it can be used to explore trade-offs between material selection and ventilation strategies. Oak, pine and maple (*Table 3*), as well as panel products OSB and plywood, are included in the database.

**Table 3** Typical volatile compounds found with solid wood

| | |
|---|---|
| **Oak** | Acetic acid, octanal, nonanal, decanal |
| **Pine** | $\alpha$-pinene, camphene, $\beta$-pinene, p-cymene, limonene |
| **Maple** | Hexanal, nonanal, decanal |

The release of hexanal from wood has been observed to rise with increasing humidity, while the release of monoterpenes does not change[33]. Emissions from materials are moderated by environmental conditions. In broader terms we are beginning to understand the compounds in wood and their potential benefits to our wellbeing.

### 2.6. Odour

The odour of wood is typically described as pleasant, with positive associations; many consumers would preferably choose wood-based products over those made from synthetic materials. Despite its general positive appreciation, however, the exact nature of wood odour is largely unresolved. Schreiner et al. reviewed the characterisation of wood odorants and their physiological effects[34], including $\alpha$-pinene and its calming effect and fir oils and their anxiolytic effect. Such relaxing effects have similarly been demonstrated in other trials. The essential oil of Siberian fir (*Abies sibirica*), for example, was observed to reduce the stimulation level in panellists when performing visual exercises, as indicated by electrocardiogram and electroencephalogram signals[35].

### 2.7. Indoor air quality and preservative-treated wood

A study by BRE commissioned by the Wood Protection Association helped provide information on preservative pre-treated timber in the context of indoor air within the construction industry[36]. The review considered industrially pre-treated wood products that have been impregnated with a wood preservative formulation for use in 2017 new-build UK domestic construction. Preservative-treated timber may be present in a number of construction product applications in our homes, including parts of the structural timber frame, window frames, tiling battens and the roof structure. Emissions studies conducted on treated timber are limited, almost certainly because preservative-treated wood products are not found in the living space of buildings.

In a 2007 UK study, timbers treated with different new-generation UC3 wood preservatives were tested for emissions in a cabin, replicating a room and wall structure[37]. The study found that 'the tests showed that the effect of emissions from the treated wood on indoor air quality of a test cabin building was negligible'. It was noted that due to low volatility of active substances, the emissions test was extended for up to 65 days to check long-term emissions from the treated timber. The study showed that the impact on indoor air quality of timber treated with the new-generation preservatives is low.

Some wood preservative active ingredients and other organic compounds and their respective boiling points are presented in *Table 4*. It is important to add to this that evaporation to air may be reduced if the material is fixed in or adsorbed into the wood substrate.

**Table 4** Boiling points of some wood preservative active ingredients and other compounds

| Chemical name | CAS number | Boiling point (°C) |
|---|---|---|
| Tebuconazole | 107534-96-3 | 476.9 |
| Permethrin | 52645-53-1 | 200 |
| Propiconazole | 60207-90-1 | 180 |
| Acetic acid | 64-19-7 | 118 |
| Formaldehyde | 50-00-0 | –19 |

Indoor air quality regulations do not include treated timber and its active ingredients, perhaps because it is not in direct contact with indoor air. The limited scientific evidence suggests that emissions from treated wood articles to air are small and that the complexity of the pathway from the treated product to the indoor air compartment means that the concentration reaching indoor air is negligible. The review[36] recommends considering further research and testing to add to the existing knowledge.

## 3: Regulations and certification

### 3.1. Standards

In the UK and elsewhere the energy efficiency of buildings has been a primary focus for decades. BS EN 15251[38] comes from a ventilation and energy perspective but notes that an energy declaration without a declaration of indoor environment quality makes no sense. This standard responds to the evidence that poor indoor environments can often have considerably higher costs for the employer, building owner and society than the costs of energy used. ISO 17772-1:2017[39] considers the indoor environment quality as part of the building energy performance.

Emissions testing of construction products is typically conducted according to ISO 16000-9:2006[40] (environmental chamber method) and ISO 16000-10:2006[41] (emissions cell method), and the determination of VOCs is by ISO 16000-6[42]. More comprehensive indoor air quality would be concerned with testing particulates (ISO 7708 (1995))[43], carbon monoxide (ISO 4224 (2000))[44] and ozone (ISO 13964 (1998))[45].

Construction products emission standards should have tests conducted to the following European or internationally recognised standards. For testing of formaldehyde emissions from wood-based products, BS EN 717-1:2004[46] is used, and the flask method in BS EN 717-3[47] can also be used for routine testing of formaldehyde release from products. For adhesives there is a general procedure in BS EN 13999-1:2013[48], and a procedure for determination specifically of volatile di-isocyanates in BS EN 13999-4:2007[49].

BS EN 13986:2004[50] is used for evaluation of conformity and marking of wood-based panels used in construction. Products included in this standard are intended for internal and external use as structural and non-structural components, and as structural floor and roof decking on joists and structural wall sheathing on studs. It comprises the emission rate of formaldehyde tested under the standard BS EN 717-1 (for final products testing), from which material may be classed as E1 or E2 according to their formaldehyde emissions range.

CEN/TS 16516:2013[51] implies the emissions testing of construction products in a 'European reference room'. The room is an environmental chamber with 30m$^3$ of nominal volume with temperature, relative humidity and ventilation conditions controlled. The standard climate and ventilation conditions are 23°C, 50% relative humidity and a 0.5 air change per hour rate.

### 3.2. Building Information Modelling (BIM)

BIM was made mandatory for Government projects in 2016 and shifted attention beyond energy efficiency to provide focus on the lifetime value of the building, of which a fundamental component is the health and wellbeing of building users and occupants.

Monitoring of building environmental data and occupant data combined with visualization and BIM opens up new possibilities to deliver improvements to people's health and wellbeing, creating healthier buildings. Birmingham City University (BCU)[52] are leading the way for healthcare buildings with an ambitious project focusing on connecting Digital BIM 3-D models with building performance data, building users data and workflow data in real-time based on the whole management of healthcare facilities. The focus of optimising performance based on real-time evidence to improve user satisfaction, comfort and ultimately 'building purpose' (in this case patient quality of care and outcome) should be central tenets for all buildings.

For construction products BIM can provide a new opportunity to specify on the basis of contributing to health and wellbeing. This might be related to the VOC emissions of products or, in future as more is quantified, the aesthetic and comfort aspects of products and their contribution to building interiors.

## 3.3. Building Regulations

Part F of the UK Building Regulations does not say anything specifically about health or define healthy indoor air. It does not cover emissions from building products, other than mentioning them in *Approved Document F* (F1 Means of ventilation – clause 4.30 to ensure ventilation is adequate to limit pollutant concentrations). CIBSE is updating *Technical Memorandum TM40 Health & Wellbeing*, to define individual pollutant limits as far as possible. The guidance indicates that TVOC should be less than 300μg/m$^3$ in line with BREEAM and HQM (Home Quality Mark). As more emphasis is put on source control to manage indoor air quality as well as adequate ventilation rates, it is anticipated that Part F will be updated.

*Approved Document L*, L1A Conservation of fuel and power in new buildings promotes increased airtightness standards in buildings; while mechanical ventilation and heat recovery units are often part of this approach, there is a gap in evidence on the impact on indoor air quality and pollutants, especially from occupants' habits, cleaning, furniture and fit-out.

A situation that might change is that the UK has no requirement for materials producers to provide emission classifications for their products. Test data can be requested from producers; it should be available as other European countries (e.g. Germany, France, Belgium) do have requirements for emissions classification. The source control and awareness of emissions from products and materials is an important starting point. In construction, bringing together many materials in combination in a designed building, there is a need to test the actual air quality within the building. This is especially relevant as building certification schemes set thresholds, and for homes there are test compliance levels stated. For example, the Education & Skills Funding Agency provides guidance on ventilation, thermal comfort and indoor air quality in schools[53].

## 3.4. Certification schemes

Whole-building assessment schemes are prolific across the globe, with perhaps 20 schemes worldwide. *Table 5* provides an overview of how five of these promote healthy buildings, directly and indirectly.

Specifically considering healthy buildings, there are several schemes and approaches open for assessment and use with a health and wellbeing focus (*Table 6*).

The final tier (*Table 7*) are healthy materials specifications, which can help contribute to delivery of healthy buildings. While this is not covered in detail in this publication, it is a starting point that many consider as the building blocks for creating a healthy building.

**Table 5** Whole-building assessment methodologies and their link to healthy buildings

| Scheme | Description | How it works for healthy buildings |
|---|---|---|
| **BREEAM** (Building Research Establishment Environmental Assessment Method) | The world's oldest whole-building assessment methodology and certification scheme, with nearly 600,000 buildings certified in 77 countries and a further two million projects in process. Health & Wellbeing credits directly drive towards healthy buildings by setting indoor VOC thresholds, having user control of lighting and thermal and acoustic comfort. Drives for healthier environments, especially considering water, transport, ecology, land use and eliminating waste and pollution. www.breeam.org | A project (building, refurbishment) is registered for assessment, assessed by qualified BREEAM assessors at design stage and delivery stage and, if using BREEAM In Use, during operation. The project is rated as Good, Very Good, Excellent or Outstanding.<br>Credits of relevance for healthy buildings are:<br>Hea 01 Visual comfort<br>Hea 02 Indoor air quality<br>Hea 03 Safe containment in laboratories<br>Hea 04 Thermal comfort<br>Hea 05 Acoustic comfort<br>Hea 06 Safety and security |
| **LEED** (Leadership in Energy & Environmental Design) | LEED provides a framework to create healthy, highly efficient and cost-saving green buildings. As a building rating system, it dominates in North America through deployment by the USGBC, and has certified 2.4 million square foot of buildings across the world. V4 focuses on materials to get a better understanding of what is in them and the effect those components have on human health and environment, as well as a stronger performance-based approach to indoor environmental quality (IEQ). new.usgbc.org/leed | LEED v4 includes an expanded focus on materials, going beyond looking at total amount used to evaluate the impact on human health and the environment. Requirements and options within the IEQ section balance the need for prescriptive measures with more performance-oriented credit requirements. The low-emitting materials credit is performance-based and measures the actual emissions from the product instead of only VOCs. |
| **HQE** (Haute Qualité Environnementale) | French certification for building construction and management as well as urban planning. HQE includes life cycle analysis at the building scale and impacts of a project on health, personal comfort and the indoor environment. It is operated by Cerway outside of France. www.behqe.com/home | HQE covers residential and non-residential buildings, including aspects of space quality, air quality and comfort (visual, acoustic, olfactory and hygrothermal). |
| **DGNB** (Deutsche Gesellschaft für Nachhaltiges Bauen) | The DGNB system is a uniform evaluation method that takes all aspects of a sustainable building into account, also allowing for adjustments to match individual types of buildings or different requirements. The scheme most frequently used is 'New Construction Offices', which currently encompasses 37 assessment criteria broken down into six areas of activity. www.dgnb-system.de/en/ | DGNB criteria "Sociocultural and functional quality" (SOC1.1) gives users of buildings the greatest possible control over indoor climate conditions, increasing their individual wellbeing.<br>SOC1.2 Indoor air quality<br>SOC1.3 Acoustic comfort<br>SOC1.4 Visual comfort<br>SOC1.5 User control<br>SOC1.6 Quality of indoor and outdoor spaces<br>SOC1.7 Safety and security<br>SOC2.1 Design for all |
| **HQM** (Home Quality Mark) | HQM is a UK national standard for new homes, which uses a simple five-star rating to provide impartial information from independent experts on a new home's design, construction quality and running costs. HQM will also show the impact of the home on the occupants' health and wellbeing, as buildings become more airtight, respiratory conditions rise and our population gets older. It will demonstrate the home's environmental footprint and its resilience to flooding and overheating in a changing climate. In addition, HQM will evaluate the digital connectivity and performance of the home as the speed, reliability and connectivity of new technology becomes ever more critical. www.homequalitymark.com | Independent, fully trained and licensed professionals assess and score wide-ranging aspects of a new home to give an overall quality rating. To provide greater clarity on how the home performs, indicators based on the key interests of the major participants – such as home occupants, developers and planners – are also rated. Indicators from a householder perspective, for example, are householder costs, positive impact on health and wellbeing and environmental footprint. |

**Table 6** Whole-building health and wellbeing schemes

| Scheme | Description | How it works |
|---|---|---|
| **WELL Building Standard** | The International WELL Building Institute (IWBI) is a public benefit corporation whose mission is to improve human health and wellbeing in buildings and communities across the world through its WELL Building Standard (WELL). The standard covers themes in detail on air, water, nourishment, light, fitness, comfort, mind and innovation. WELL was developed by integrating scientific and medical research and literature on environmental health, behavioural factors, health outcomes and demographic risk factors that affect health, with leading practices in building design, construction and management. www.wellcertified.com | Launched in October 2014 after six years of research and development, the WELL Building Standard is the leading standard for buildings, interior spaces and communities seeking to implement, validate and measure features that support and advance human health and wellness.<br>Projects registered are assessed and commit to improvements and continued engagement monitoring. |
| **Fitwel** | The Center for Active Design (CfAD) is a not-for-profit organisation that works at the intersection of health and the built environment. Over the last five years their work has gone global, reaching over 180 countries and informing the design of buildings and public infrastructure projects around the world. The Fitwel Certification System provides a standard for the building industry, supporting widespread adoption of health-promoting strategies through a user-friendly digital portal. The Centres for Disease Control and Prevention remains the research and evaluation partner. www.fitwel.org/ | The Fitwel Scorecards include 55+ evidence-based design and operational strategies that enhance buildings by addressing a broad range of health behaviours and risks. Each strategy is associated with unique point allocations, based on the strength of associated evidence and the demonstrated impact on occupant health. This means that strategies with stronger, multifaceted impacts receive more points. Fitwel addresses health as an interconnected system, with no single dominant category or area of focus, and as such all strategies are voluntary, with no individual prerequisites. |
| **Baubiologie** | Building biology is a healthy building philosophy developed in Germany. It investigates the indoor living environment and how buildings can affect the health of the occupants. Important areas of building biology are materials and processes, electromagnetic fields, radiation and indoor air quality. The Institute of Building Biology + Sustainability or IBN (Institut für Baubiologie + Nachhaltigkeit) was founded in 1983. Its services include:<br>• research and training in building biology<br>• assessment of building materials, equipment, homes and properties<br>• inspections of buildings according to the Standard of Building Biology Testing Methods<br>www.buildingbiology.com/ | **Building Biology Standard**<br>The Standard of Building Biology Testing Methods SBM-2015 gives an overview of the physical, chemical and biological risks encountered in sleeping areas, living spaces, workplaces and on properties. It offers guidelines on how to perform specific measurements and assess possible health risks. In addition to this, there are also detailed building biology testing conditions and testing methods.<br>**Building Biology guideline values**<br>The Building Biology Evaluation Guidelines are based on the precautionary principle. They are specifically designed for sleeping areas associated with long-term risks and a most sensitive window of opportunity for regeneration. They are based on the experience and knowledge of the building biology community and focus on achievability. |
| **World Green Building Council (WGBC) guidance** | Three pivotal reports from the WGBC provide guidance on health in offices[54], retail[55] and the business case[56]. The overwhelming evidence is that design significantly impacts the health, wellbeing and productivity of staff.<br>Findings for offices include:<br>*Indoor air quality*: a comprehensive body of research suggests that better indoor air quality (low concentrations of $CO_2$ and pollutants and high ventilation rates) can lead to productivity improvements of 8–11%.<br>*Thermal comfort*: a significant impact on workplace satisfaction and modest degrees of personal control over thermal comfort can return improvements in productivity.<br>*Lighting and views of nature*: productivity gains come from proximity to windows; views from windows are probably the more significant factor, particularly where the view offers a connection to nature.<br>*Noise and acoustics*: noise provides an unwanted distraction. This can be a major cause of dissatisfaction among occupants.<br>*Interior layout*: workstation density, breakout space and social space have an impact on concentration, collaboration, confidentiality and creativity.<br>*Active design and exercise*: access to services and amenities such as gyms, bicycle storage and green space can help to encourage healthier lifestyles among building occupants. www.worldgbc.org | The *Health, Wellbeing and Productivity in Offices* report presents a simple toolkit that businesses can use to measure the health, wellbeing and productivity of their buildings and inform financial decision-making.<br>The toolkit to measure health, wellbeing and productivity includes:<br>*Financial metrics*: absenteeism, staff turnover, revenue breakdown (by department or per building), medical costs and complaints and physical complaints.<br>*Perceptual metrics*: studies that test a range of self-reported attitudes into health, wellbeing and productivity in the workplace can contain a wealth of information for improving office performance.<br>*Physical metrics*: direct measures of the physical office environment, such as temperature, are key to measuring the effect on the health, wellbeing and productivity of workers. Exciting developments in this area, such as portable and wearable technology, are likely to substantially expand our understanding |

**Table 7** Healthy materials certifications and schemes

| Scheme | Description | How it works |
|---|---|---|
| **Ecolabels** | Generated initially as a form of distinction for green products in consumer and commercial arenas, there are now over 150 ecolabels for products globally, such that ISO 14024[57] was created to define descriptions to provide some uniformity. As many require a statement about VOC emissions from the product they sometimes consider a de facto healthy product mark. The French Décret[58], Belgian Décret[59] and AgBB[60] (Germany) are national legislations that require ecolabels and evidence of emissions. | Mostly local relevance that does not transfer well across borders and regions. Blue Angel[61], Nordic 'Swan' Ecolabel[62], Natureplus[63] and CARB[64] are Type 1 ecolabels relevant to timber products where some market success has been achieved in the UK. The EU Ecolabel[65] is not applicable to timber products. |
| **Portico** | A healthy materials curated library application that Google developed in partnership with the non-profit partner Healthy Building Network (HBN). The Google Portico online tool was created to identify the healthiest products and materials for every Google building around the world. Portico allows manufacturers and project teams to collaborate with each other and deliver healthy and high-performing buildings at scale.<br>healthybuilding.net/products/portico | Scores the building product, employing the material health and transparency criteria. There are three main functions that are performed in the Google Portico app: project management, product research and product information requests. The product library has more than 2,500 products. Products are assessed against more than 40,000 chemical hazards sourced from the HBN's Pharos Project, allowing comparison of materials for health and environmental hazard screening and certification information. |
| **HPD** | The HPD Open Standard is a standard specification for the accurate, reliable and consistent reporting of product contents and associated health information, for products used in the built environment. A Health Product Declaration® (HPD) can be created using the standard. The HPD Open Standard specification is harmonised with programmes of the International Living Future Institute, Cradle-to-Cradle Product Innovation Institute, Clean Production Action, BIFMA, LEED, WELL and a growing number of rating and certification standards in the building industry.<br>www.hpd-collaborative.org/hpd-open-standard/ | The collaborative is a not-for-profit, member association with over 250 organisational members, representing the full spectrum of the building industry: architects, designers, building owners, manufacturers, consultants, tool developers, standards programmes and others who all share a common purpose to improve the transparency of information and the material health of the built environment. Using a consensus-based, stakeholder process, HPDC members create, support and evolve the HPD Open Standard. |
| **PhD**[66] | The Global GreenTag Product Health Declaration™ is the first of its kind in the world – a certification tool that recognises progressive manufacturers who fully disclose with 100% transparency the toxicity information of their products. Since the launch of the GreenTag PhD™ in March 2017, Global GreenTag PhDs now have formal WELL™ Building Standard Equivalencies and recognition in LEED. | FEATURE 04: VOC reduction; PART 1: Interior paints and coatings; PART 2: Interior adhesives and sealants; PART 3: Flooring; PART 4: Insulation; PART 5: Furniture and furnishings<br>FEATURE 11: Fundamental material safety PART 1a: Asbestos restriction<br>FEATURE 26: Enhanced material safety: PART 1: Precautionary material selection<br>FEATURE 97: Material transparency, PART 1: Material information |
| **C2C**[67] | The Cradle to Cradle Certified™ Product Standard guides designers and manufacturers through a continual improvement process that looks at a product through five quality categories – material health, material reutilisation, renewable energy and carbon management, water stewardship and social fairness. The Cradle to Cradle Certified™ mark provides consumers, regulators, employees and industry peers with a clear, visible and tangible validation of a manufacturer's ongoing commitment to sustainability and to their communities. | The institute administers the publicly available Cradle to Cradle Certified™ Product Standard, which provides designers and manufacturers with criteria and requirements for continually improving what products are made of and how they are made. |

### 3.5. Construction Products Regulations and certification schemes

The Construction Products Regulations 2013 (CPR)[68] essential requirement number 3 is hygiene, health & environment. Environmental sustainability has dominated products and energy efficiency for buildings. CPR for materials health draws attention to indoor emissions and reducing or eliminating them at source. Low- to no-emission products make good sense, given the longevity of use of the product in the building and the time we spend indoors. Not all VOCs are harmful and some may even have positive therapeutic impacts – there are natural VOCs that can have a positive impact (*Section 2.5*).

The movement towards natural buildings is laudable but we should also recognise that non-natural materials and chemicals also play vital roles in our buildings, ensuring long-term performance, weather protection, aesthetic appeal and moisture control, while providing lightweight repeatable designs for offsite manufacture. Timber features as a core component of all-natural buildings; it features qualities we are just beginning to understand while providing a connection to nature, yet is also industrially useful, lending itself to lightweight offsite home manufacture, circularity of use and tall buildings.

*Table 8* shows the TVOC and formaldehyde emissions limit required by several certification schemes across Europe.

Timber as a construction material is highly versatile and deployed in almost every product category within our built environment – as solid wood, particles or fibres. Its chain of custody credentials, the social value of forest assets, the momentum around low-carbon impacts and the ability to store carbon in our built environment are all positives and provide a favourable market position for timber. It is our oldest construction material, yet we continue to learn of its qualities. Now investigations are starting to show the role timber can have in the delivery of healthy buildings, creating positive, energising and restorative interior environments that will help us relax, rest, work, learn and heal more effectively.

**Table 8** Limit values emissions testing in a ventilated test chamber required by various regulations and schemes. Materials and health and timber in certification and products schemes

| | TVOC (µg/m³) | Each carcinogen C1A,CA2 (µg/m³) | Formaldehyde (µg/m³) | Products and notes |
|---|---|---|---|---|
| Belgian regulations[69] | 1,000 | 1 | 100 | All construction products used as flooring, or as support or for installation of floors. This includes coatings, adhesives and screeds. |
| French regulations class A+[70] | 1,000 | –/– | 10 | Flooring, walls and ceilings, insulation materials, doors, windows and any other construction product installed indoors. |
| French regulations class A[71] | 1,500 | –/– | 60 | |
| French regulations class B | 2,000 | –/– | 120 | |
| French regulations class C | >2,000 | –/– | >120 | |
| German AgBB regulation[72] | 1,000 | 1 | 100 | Construction products installed indoors.<br>The selection of low-emission construction products may lay the foundation for low-concentration indoor environments. Such products can be recognised by environmental labels (e.g. the 'Blue Angel'), by product identification (e.g. the EMICODE for installation materials) or also by approval tests according to the test criteria of the Committee for the Health Assessment of Construction Products (AgBB). After completion of the building, the positive result of a corresponding product choice must be demonstrated by measurement. |
| EMICODE[73] EC1$^{PLUS}$ | 60 | 1 | 60† | Flooring and walls. This includes liquid products, mineral products, resins, underlayers, joint sealants, joint insulations, joint sealing tapes and surface coatings for wood floorings. |
| EMICODE EC1 | 100 | 1 | 100† | |
| EMICODE EC2 | 300 | 1 | 300† | |
| Blue Angel<br>RAL UZ 156[74] | 300 | 1 | 60 | Flooring insulation underlays |
| Blue Angel<br>RAL UZ 176[75] | 300 | 1 | 60 | Wooden floorings, boards and doors |
| LEED v4 | 500<br>200 | | 27<br>16.3 | Materials: understanding what is in them and the effect those components have on human health and the environment. It uses a performance-based approach to indoor environmental quality for better occupant comfort.<br>Inherently non-emitting sources: products that are inherently non-emitting sources of VOCs (including unfinished or untreated solid wood) are considered fully compliant without any VOC emissions testing if they do not include integral organic-based surface coatings, binders or sealants. |
| WELL v2 | 500 | | | Preconditions (A01, M02) and optimisations (A05, L06, T07, X10, M07)<br>**AIR** A01 fundamental thresholds for organic and inorganic gases<br>A05 enhanced thresholds for organic and inorganic gases<br>**LIGHT** L06 Visual balance Part 1 Managing brightness<br>**THERMAL COMFORT** T07 Humidity control<br>**MATERIALS** X10 Volatile compound reduction<br>**MIN**D M02 Access to nature Part 1 Provide access to nature. Indirect connection to nature through use of natural materials, patterns, colours or images<br>M07 Restorative spaces Part 1 Provide restorative indoor spaces |
| BREEAM and HQM | 300 | | 100 | Indoor air quality. Not specific for a construction product |

† 3 day emissions

## 4: The evidence for using timber and wood products within healthy buildings

In a review of wood and human stress in the built indoor environment presented by Burnard and Kutnar, the authors argue that 'creating healthful indoor environments should be a priority for building designers, and evidence-based design decisions should be used to ensure the built environment provides benefits to occupants'[76]. To date, studies examining the psychophysiological effects of wood use in interiors have revealed reduced autonomic stress responses when compared to rooms without and with less wood. There is a need to better understand the psychophysiological responses to wood, and the authors suggest specific aspects of wood, such as colour, quantity and grain pattern, should be examined in more detail.

An extensive literature review conducted by Nyrud and Bringslimark examined whether interior wood use was psychologically beneficial[77]. They concluded that people value the natural qualities of wood, with similarities in preferences for wood because of this feature, and there seem to be some indications of beneficial effects.

The *Workplaces* report by Pollinate found that most Australians lead increasingly indoor lives and have limited opportunities to connect with nature in their everyday activities (*Figure 3*)[78]. There are benefits in simulating this important connection using wood and biophilic design in the built environment. A survey of 1,000 'typical' indoor Australian workers was conducted and resulted in the following key findings:

- around two-thirds of indoor workers spend most of their work day in an office environment
- around half spend an hour or less outdoors each day
- over one-third are not satisfied with their physical working environment
- the majority use negative words such as 'enclosed' and 'dull' to describe their workplaces
- over one in four take unplanned leave when they are physically fit
- workers who are satisfied are less likely to take unplanned leave, and have fewer sick days
- workers in workplaces with more wood have higher levels of satisfaction
- biophilic design elements (plants, natural light) correlate with increased workplace satisfaction
- workers in work environments with exposed wood feel more connected to nature and have more positive associations with their workplace
- workers in wooden working environments have higher levels of wellbeing and take less leave
- wood is correlated with higher levels of concentration, improved mood and personal productivity.

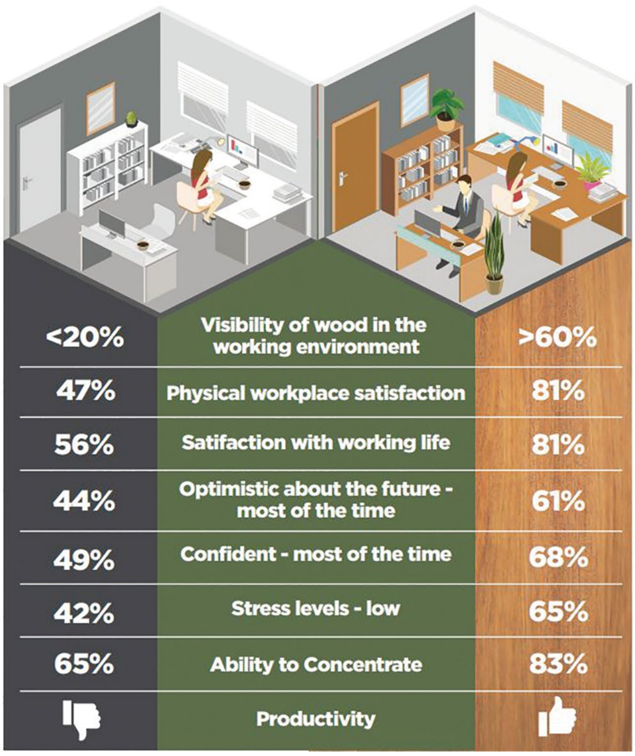



**Figure 3** Benefits of wood in the workplace
Image: Forest and Wood Products Australia Ltd

### 4.1. Perceptions of wooden surfaces and 'wood preference'

Consumer perceptions of wood were examined by Jonsson et al., who considered solid wood, wood-based panels and composites[79]. Principal component analysis generated two factors describing (1) naturalness, wood-likeness, softness, unprocessed origin, living, pleasant and high value; and (2) solid and homogeneous impression. A third, preliminary factor included categories describing irregular pattern, sleekness and smoothness. The solid wood samples were most liked by consumers. Preferred core categories were naturalness, wood-likeness, smoothness, living impression and value.

Wood in building interiors is popular among the public; growth in wood flooring sales over the last 15 years is testament to that. In general, people have positive attitudes towards wood and interior wood use. Wood is commonly perceived as natural, warm and healthy, and is often preferred over other materials. Nyrud and Bringslimark noted that attributes that can influence aesthetic preferences do correspond with some of the preferred physical properties of wood, namely complexity, coherence and naturalness[80].

An investigation by Lyytikäinen at the University of Finland hypothesised that the use of interior decorative wood surfaces may bring to building occupants the relaxing qualities associated with exposure to nature[81]. The research focused on the restorative effect of engineered wooden surfaces (glulam, plywood, MDF, OSB). People's preferences towards wooden surfaces for both haptic and visual sensations were explored with open questions for participants about the potential use of each wood material and a stress test. The stress test aimed to examine whether the participants' heart rates and blood pressures lowered as they experienced the haptic and visual effects of wood material, and if there were differences between different materials. Visual sensations were observed to have more dominant effect than haptic sensations on the participants' preferences. Both heart rate and blood pressure lowered from the start of the test with all the wood materials except OSB.

The *Planet Ark Wood Housing Health Humanity* report explored the use of wood in the interior of a building as having clear physiological and psychological benefits that mimic the effect of spending time outside in nature[82]. The feelings of natural warmth and comfort that wood elicits in people have the effect of lowering blood pressure and heart rates, reducing stress and anxiety, increasing positive social interactions and improving corporate image (*Table 9*). These benefits are particularly important for environments in which it is difficult to incorporate nature indoors, such as hospitals where strict health and safety guidelines may prevent the presence of plants, and office environments where views from the window are of roads and neighbouring concrete buildings. An update in 2016 showcased numerous nature-connected design exemplar buildings[83].

Wood is generally associated with being practical, aesthetic and economy-friendly. Using wood in interior settings can be based on psychological expectations and assumptions, as wood is considered to be warmer, homely, more relaxing and more inviting. Usually wood is compared to carpets, glass, leather, stone or plastic, but is not compared to a visually similar material such as laminate. Jiménez et al. analysed and compared the psychological characteristics related to wooden and laminate materials in interiors[84]. Their results show that wooden floors were evaluated as significantly better than laminate floors regarding 'atmosphere' and 'values and symbolic functions'. For the criterion 'health', a tendency in favour of solid wood was also found. The results further show that the psychological aspects related to the wood material were evaluated to be significantly better than those of the laminate material.

A study in New Zealand by Ball et al. presented images of modern corporate interiors to people[85]. Five of the interiors significantly featured wood, while the other five featured no wood at all. Participants were asked to 'identify the organisation you would most like to work for and least like to work for', followed by selecting three adjectives from a list to indicate their first impressions of each organisation. The presence of wood products within a corporate environment drastically influenced first impressions, with subjects significantly more likely to want to work for organisations that featured wooden fit-out and furnishings. Offices with wooden interiors conveyed feelings of innovation, energy and comfort, while offices without wood conveyed feelings of being impersonal and uncomfortable.

**Table 9** Results of the Planet Ark survey asking how participants perceive different material types (score out of 100)

| Material | Perception | | | | | |
|---|---|---|---|---|---|---|
| | Creates a natural look and feel | Creates a warm and cosy environment | Visually appealing | Feels nice to touch | Environmentally friendly | Relatively cheap |
| Wood | 93 | 92 | 88 | 87 | 68 | 31 |
| Brick | 61 | 62 | 58 | 30 | 47 | 30 |
| Concrete | 25 | 23 | 24 | 20 | 27 | 35 |
| Steel | 20 | 16 | 36 | 36 | 28 | 20 |
| Aluminium | 17 | 15 | 33 | 34 | 30 | 36 |
| Plastic | 14 | 18 | 24 | 36 | 14 | 71 |

The Wood2New project looked at new design strategies, focusing on implementing the psychologically beneficial effects of nature in the built environment, which are increasingly being implemented in building design[86]. The design of built settings is of importance in environments intended for healing, such as hospitals. Preferences for a setting are thought to be indicators of factors in the environment that can enhance health and wellbeing for both patients and those who care for them. Nyrud et al. investigated preferences for natural construction materials in patient rooms[87]. An online survey was distributed to one department at a Norwegian hospital. In the survey, patients and medical staff were asked to evaluate computer-manipulated images of patient rooms with different amounts and dispositions of wood on surfaces – a room that had no wood present, some wood present and a lot of wood present (walls, floor, ceiling, furniture). The room with some wood present was preferred, then the room without any wood, and the room with a lot of wood was liked least. The results indicate that there are limits to how much wood is preferred and they provide some guidelines for how wood should be used in interior settings.

Strobel et al. reported on focus groups carried out in Austria, Finland, France, Norway and Sweden to understand building professionals' and laypeople's perceptions of building materials and wellbeing in indoor environments[88]. The main objective of the focus groups was to explore how the use of wood is perceived in interior environments. Participants' responses were linked to the physical properties of wood: density, hardness, grain, thermal conductivity, moisture content, chemical composition, colour and natural origin. Based on the discussion, these physical properties can be related more closely to the perception of wood as a natural material with respect to intended use, such as visual and tactile products.

The complexity of human studies can provide some rather contradictory evidence that is almost certainly an outworking of the experimental methodology, study size, material use and duration. It is also a reflection of our growing knowledge of the impacts wood interiors can have – they can be relaxing and calm but also stimulating and exciting. For example, Tsunetsugu et al. studied the visual effects of interior design in living rooms on physiological responses[89]. Cerebral blood flow, pulse rate and blood pressure were measured while the subjects spent 90 seconds in the rooms. The two test rooms caused different physiological responses, i.e. the room with an ordinary interior design caused a calm and relaxed state, while the other room with visible wooden posts and beams caused an active and engaged state. It provided a more stimulating and interesting interior environment. In another study, an experiment that assessed subjective differences in feelings of wellbeing in a room equipped with walls of Japanese cedar wood compared to a control conditioned room observed that liking and feeling responses of the panellists were significantly different between the two conditions, with a preference for the wood-walled room[90].

Sakuragawa in Japan quantified the impact of visual stimulation from interior wood finishes on the impression of room interiors, and user feelings[91]. Four types of room interiors with interior wood finishes used in different proportions were simulated. A great desire for calmness was obtained from photographs showing wood materials. In an evaluation of 'living', the photograph of a room interior without wooden materials was evaluated as a place that test subjects did not feel like living in. The photograph showing wood materials used only as flooring material was evaluated as the place that test subjects most felt like living in and considered most suitable as a living space. This points to there being a balance of some wood products in interiors, as Nyrud et al. found in the hospital room[92].

## 4.2. Physiological and psychological benefits of wood

### *4.2.1. Education*

Kelz et al. studied the use of wood in classrooms in Austria and found that over the course of a school year pupils' heart rates significantly decreased in the solid wood classroom but increased in the control classroom[93]. Also, perceived stress from interactions with teachers (being shouted at, being ignored) decreased significantly over the school year in the solid wood classroom, while it did not change for pupils in the control classroom. This study did not find significant differences or changes over time in pupils' concentration performances. It is assumed that the reduced perceived stress and reduced heart rates are positive contributions to the pupils, staff and the education system. The study is known as the School without Stress[94], and examined school students in the Hauptschule Haus im Ennstal who were taught in either a classroom furnished with floors, ceilings, cupboards and wall panels made of solid wood or a classroom fitted with a linoleum floor, plasterboard walls and chipboard cupboards. In the solid wood classes heart rates were reduced by an average of 8,600 beats per day. The pilot study by proHolz, the Arbeitsgemeinschaft der Holzwirtschaft and the vice-mayor and mayor of Haus im Ennstal has shown results that could revolutionise school construction in that region.

**Figure 4** The Enterprise Centre at The University of East Anglia was the first large scale commercial building in the UK to achieve both Passivhaus standard and BREEAM Outstanding rating

Photograph: © Dennis Gilbert

Pervanidou and Chrousos reviewed the metabolic consequences of stress during childhood and adolescence[95]. The experience of acute stress may lead to the development of several conditions, including anxiety disorders, depression, obesity and metabolic syndrome. The benefits of a timber-rich teaching environment provide encouragement for its increased use in educational settings. The results indicate that the use of solid wood in classrooms can reduce pupils' stress levels, and this is influencing local decision-making. The promising results should be replicated with more subjects and different age groups to build upon this exciting finding.

### *4.2.2. Healthcare*

In a study by Anme et al. in Japan it was concluded that wood products improve the quality of life of elderly people in assisted living accommodation[96]. The participants in the study were 44 elderly people and 30 health and social care professionals in a single assisted living facility. Independent evaluators and professionals observed and rated the elderly people's behaviour. The results indicate that regular use of wood products significantly increased social interactions and harmonious relations, activity levels and mental energy in elderly people. Thus, using wood products on a daily basis appeared to improve the quality of life of elderly people by stimulating emotional relationships through improved cognitive function. Social interactions that lead to opportunities for self-expression in old people reduce the risk of dementia, a disease that currently affects 850,000 people in the UK and over 50m people worldwide.

A Canadian study has demonstrated that the colours and texture of wood elicit feelings of 'warmth', 'comfort' and 'relaxation' in people[97]. The findings suggest that people's responses to wood are, for the most part, extremely positive, with subjects generally showing a strong preference for rooms containing many wood details. There also appears to be a strong belief that the use of wood can help to create healthful environments, and commonly evoked descriptors for wood rooms in this study include 'warm', 'comfortable', 'relaxing', 'natural' and 'inviting'.

Augustin and Fell considered the impacts of nature views, plants, natural light and soundscapes on healthcare environments[98]. Part of the report looked at wood in healthcare environments and provides a comprehensive summary, including self-reported studies by Japanese researchers who are actively engaged in the field. Psychophysiological response to wood was studied by Fell in his PhD studies, specifically the autonomic responses of 119 subjects in wood and non-wood offices before, during and after a stressful mental task[99]. In this study, sympathetic nervous system activation was lower in the wood room, indicating lower stress. Skin conductance level was also lower in the wood office when subjects were alone in the room. Further, the rate of non-specific skin conductance responses, measuring divergent stressful thoughts, in the wood office was less than half that in the non-wood office.

Stephen, at the University of British Colombia, concluded that the research in this field, while growing, is in its relative infancy, that long-term studies are scarce and inclusion of wider demographics is required – too often students are the volunteers in studies[100].

### *4.2.3. Office workplace*

A study carried out by Fell found that the visual presence of wood in an office-like room lowers sympathetic nervous system (SNS) activation in occupants, which is best known for regulating stress responses such as increased blood pressure and heart rate[101]. Fell confirmed that this sensation of relaxation in the presence of nature is due to a reduction in stress reactivity in our SNS, which is both psychologically and physiologically beneficial.

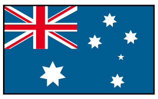
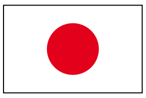
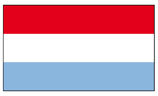
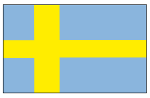
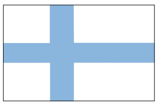
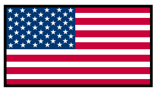
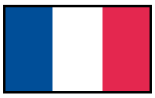
Results indicate that the use of wood in an office interior fit-out led to an overall more favourable first impression by the occupant[102]. Work at FPInnovations at the University of British Colombia, under the leadership of Fell revealed much about our preferences for wood[103]. Four office environments varying in degree of wood finish were created to study the effects of natural materials in the built environment on autonomic nervous system responses. Stress as measured by SNS activation was lower in the wood room in all periods of the study. Workplace research by furniture manufacturer Knoll in 2014 cites Fell's work and observes that the physiological benefits of wood for offices holds key implications for businesses, including happier workers, lower staff turnover, fewer stress-related illnesses and a reduction in sick days[104].

As well as project efficiency, safety and environmental benefits of wood, the health benefits were highlighted in a case study by Ankrom Moisan Architects when they designed their own office using wood at 38 Davis, Portland[105]. The six-storey office/residential space features exposed timber and glulam and wood furnishing and fit-out components. Occupant wellbeing benefits of the project were noted as greater occupant comfort, decreasing stress and improved air quality and acoustics. They claim that wood naturally improves indoor air quality due to its hypoallergenic characteristics, from easy-to-clean surfaces to humidity moderation. Wood is naturally sound-dampening and offers excellent noise control.

### 4.3. Evidence in practice from around the world

There is worldwide interest in the use of wood in healthy buildings to promote additional psychological benefits. Some examples (*Table 10*) are noted here as the research evidence base grows and case studies continue to build.

**Table 10** Case studies of wood and healthy buildings from the around the world

| | | | |
|---|---|---|---|
| **Australia**<br> | *Wood Housing Health Humanity* report[106]<br>Dandenong Mental Health Centre<br>Marist College Bendigo, Montagne Centre<br>Melbourne School of Design<br>The Village Centre, National Arboretum, Canberra<br>Tempe House, Tempe, NSW<br>The Library at the Dock, Victoria Harbour, Melbourne | **Japan**<br> | Timber Dentistry, Minoo[107] |
| **Austria**<br> | School without Stress[108], Hauptschule Haus im Ennstal | **The Netherlands**<br> | Osteopathie Praktijk Roosendaal, Roosendaal[109] |
| **Canada**<br> | *Wood in Healthcare* report[110]<br>One Kids Place children's treatment centre, North Bay, ON<br>Critical Care Tower at Surrey Memorial Hospital, Surrey, BC<br>Thunder Bay Regional Health Sciences Centre, Thunder Bay, ON<br>Tseshaht Tribal Multiplex & Health Centre, Port Alberni, BC<br>Gateway Lodge Complex Care & Assisted Living, Prince George, BC | **Norway**<br> | Knowledge Centre, St. Olavs Hospital, Trondheim[111] |
| **Denmark**<br> | Livsrum, Cancer Counselling Center, Næstved[112]<br>Healthcare Center for Cancer Patients, Copenhagen[113] | **Sweden**<br> | Skandion Clinic, Uppsala[114] |
| **Finland**<br> | The Onni Wellbeing Centre, Pukkila[115] | **USA**<br> | The Herrington Recovery Center[116], Milwaukee, WI<br>Ankrom Moisan Architects office at 38 Davis, Portland, OR[117] |
| **France**<br> | Medical Care Centre Limay, Limay[118] | | |

## 4.4 Case studies from the UK

Wood-promoting organisations in the UK have been quick to highlight that wood lowers the human SNS activation. Wood for Good, in their summary of health and wellbeing in homes[119], noted that buildings are still being designed today that can exacerbate or even create issues like seasonal affective disorder (SAD), depression and lung disease. They report that cognitive abilities increase by 61% when in a green building. This increases to 101% when additional ventilation rates are introduced. Workers in offices with wooden interiors conveyed feelings of innovation, energy and comfort, whereas in offices without wood they conveyed feelings of their environment being impersonal and uncomfortable. Wood products in a room have also been shown to improve indoor air quality by moderating humidity.

There are several relevant case studies available on the TRADA website at www.trada.co.uk/case-studies, including:

- The Enterprise Centre, Norwich, East Anglia
- Sunbeams Music Centre, Penrith, Cumbria
- Maggie's Oxford Centre

**Figure 5** Maggie's Oldham has been designed to make the most of natural ventilation and light throughout the year
Photograph: © Alex de Rijke

- Maggie's Oldham Centre
- The Dyson Centre for Neonatal Care
- Feilden Fowles Studio
- Living Planet Centre.

In a Barbour Product Search news item in November 2017[120] the possible healthcare benefits of using timber were noted, citing Maggie's Centres and the Cranleigh Medical Centre, near Guildford. The latter also used engineered timber – the architect wanted to create an uplifting environment and the exposure of the natural timber superstructure in the communal area creates a light and natural environment to promote wellness, which has helped create a more homely welcome.

Gabrielle Golenda in Archtizer[121] compiled a collection of nine healthcare facilities that incorporate wood and other natural elements to design environments that promote physical and mental wellbeing. These include examples from the UK, Japan, Denmark, Norway, the Netherlands, Sweden and France. These intuitive uses of natural qualities including timber in the interiors, and the form of the buildings lends weight to the global phenomena of appreciating timber's ability to convey wellbeing.

## 5: Specifying timber for healthy buildings

A focus on air quality, water quality, active design, lighting, acoustic quality, materials and comfort is a way to deliver healthy buildings. Timber has significant roles to play as part of the building and fit-out, influencing light, acoustics and comfort, and is a key material for interiors for improved wellbeing. Wherever possible, timber should be considered to feature visibly in the interior of buildings, mindful of the research evidence documented in this publication that, in some cases, limitations on the amount of wood are preferred (e.g. hospital rooms). Case study evidence on the intuitive use of natural materials is producing buildings that are reported as better for patients, visitors, workers and occupiers. This is increasingly being supported by a growing evidence base of data from scientific studies.

Parameters that need to be considered when specifying timber for healthy building projects include the following.

1. **Project type (new build or refurbishment and fit-out (RFO))**
   New build has the opportunity to include a timber frame or massive timber as part of the solution, which in turn can provide interior qualities to the finished building. This was used in several examples such as the Maggie's Centres and the Dyson Neonatal Unit in Bath. Further to the qualities of timber construction as rapid, with offsite potential, using natural materials with a low-carbon impact, we can add the qualities of interior use of wood as discussed here.

   RFO is an opportunity to add timber in interiors to help change existing buildings and create more interesting, aesthetic, calm and inspiring environments. Retail, healthcare, offices and education can all deploy wood in RFO to provide an indirect connection to nature through the natural wood surfaces. It is important to ensure that health and wellbeing is on the brief of RFO projects and maintains an important role in material selection. Considerations for RFO projects include wall panelling, doors, staircases, wood flooring, finishes and colours, as well as decorative features such as wood wall art.

2. **Timber species**
   All wood species can be used in interiors, and the variety of colours and grain patterns is a distinct advantage of wood, providing an aesthetic palette for architects and designers. There is an indirect connection to nature through the natural material of wood, where pattern and diversity create interest, intrigue and stimulating spaces. In addition, different surface textures can be produced through the sawing pattern and finishing of the wood surface, creating interest in haptic wood surfaces. Wood species that are better at modulating peaks and troughs of humidity and temperature in indoor environments tend to be those that are more dynamic in moisture movement. These include the European softwoods and hardwoods such as beech.

3. **Preservatives and coatings**
   In some applications, wood preservatives, fire retardants and coatings are used to ensure the functional requirements

of the product are met. For timber this includes qualities such as aesthetics, durability, fire performance and ease of cleaning. Wherever a product is required, its possible impact on healthy building focus should be considered. These tend to be around impacts on air quality and ease of cleaning. Low- to no-VOC paints and wood coatings are to be specified and used in accordance with manufacturers' recommendations. This publication has noted that wood preservatives do not appear directly in contact with the interior compartment of buildings, and their impact on occupants is thus negligible. Specification of these should follow *WPA Manual*[122] processes and guidelines, supported by EN BS 8417[123]. Fire-retardant treatments may be present in the interior of the building and while the active ingredients are not highly volatile, work is underway to categorically conclude on this point. Specification should follow the *WPA Fire Retardant Manual*[124].

4. **Glues**
   The adhesives used to bond engineered timber products such as glulam and CLT, and used to make panel products such as OSB and plywood, like the wood itself, emit VOCs to air, especially when curing. There are low-VOC glue options and in some cases no-glue options may be possible, such as with Brettstapel using hardwood dowels to fix the wood boards together when creating the panel.

5. **Product emissions**
   The awareness of emissions from products and materials is an important starting point for communicating the value of healthy materials and construction products. The declaration of emissions from construction products is not mandatory in the UK for product manufacturers, and there is no specific scheme that is adopted to classify and communicate this. Request data from producers; it should be available as other European countries (e.g. Germany, France, Belgium) do have requirements for an emissions classification. This data is the first step of source control to enable the specifier to choose products that have low to no emissions. The data fits into the further practical design advice given by Perkins (2017)[125] in an Arup and UKGBC technical paper for working with clients that are committed to improving indoor air quality. This includes a best practice approach for identifying best in class options, how to make material substitutions to improve IAQ and post completion measurement.

6. **Specification help**
   As the momentum grows around delivering healthy buildings, specification tools will further appear to enable selection of materials. It is likely that a timber-specific tool will appear as the evidence is documented on the positive impacts wood has in interiors. Often it can be quite difficult to see what is behind the tools and specifications, so it is uncertain whether they consider the nuances of timber or not. Some of these material specification tools have been reviewed in this publication and may be useful for specific projects or comparison of materials.

   BIM provides new opportunities through the monitoring of building environmental data and creates links to improve the health and wellbeing of building users and occupants. For construction products this provides a new opportunity to be specified on the basis of contributing to health and wellbeing. This might be related to the VOC emissions of products or in future as more is quantified the aesthetic and comfort aspects of products and their contribution to building interiors.

7. **Aftermarket products**
   Studies that follow the operation of buildings note that the maintenance and care aspects of the operation have an impact on occupants. Being clean is a positive attribute of a building and there are numerous options to select low- to no-VOC products for cleaning, and environmentally responsible solutions such as biodegradable cleaning agents. Wood surfaces should not require any specific cleaning or aftercare beyond the usual redecoration cycles within buildings, especially in high-traffic environments.

8. **Monitoring impacts**
   The evidence base is growing for the positive impacts of timber in healthy buildings. More measurement of impacts in operational buildings is needed and there are several ways to encourage projects to do this. It is fundamental to ask occupants about the building and how it functions for them. Aspects of post-occupancy evaluation can be used to extract information about how the building performs before and after a refurbishment, for example. Use the building data to understand how it copes with operational differences in seasonal cycles of the building around heating, cooling and ventilation. Deployment of sensors to record aspects of air quality, light, thermal and acoustic quality can be helpful in establishing a picture of the project's indoor environment quality. An expert team should be consulted about the most

appropriate sensors to use, their accuracy, their calibration and the measurement locations.

9. **Building certification**
If the building is targeting certification for its environmental and/or wellbeing performance, consider how timber can help achieve credits, within those schemes selected, that will help the client and the building achieve its ambition. The areas where timber and wood may positively influence interior impacts have been discussed in this publication.

10. **The 'timber advantage'**
In this publication, health and wellbeing are dominant and timber has a role to play here in positively contributing to our physical, mental and social health in buildings by delivering colour, aesthetic, diversity, nature, texture, hygrothermal effects and more. This holds the prospect of an exciting future when, alongside this, timber is specified for a wide range of reasons as construction products and building systems based on its ease of use, strength to weight ratio, durability, environmental credentials, chain of custody, social values and adaptability.

## 6: The future of healthy buildings

Research examining the health effects of wood in the built environment has provided evidence of reduced stress, and improved stress recovery in the presence of wooden products. This could provide significant benefits to workers, students and others who spend so much time indoors. There is an increasing body of research evidence that is confirming anecdotal studies of the health and wellbeing benefits of using timber in buildings to contribute to healthy buildings. There is a universal need for more research as emphasised by the leading global researchers in this field, including:

- which processes are engaged in generating psychological benefits of nature in indoor settings
- the cultural and individual differences that influence preferences for wood in indoor settings
- the characteristics of the wood
- more studies to be conducted in field settings outside of the laboratory
- more longitudinal studies, to get a better picture of how benefits persist or dissipate.

These themes are reported by researchers from Norway, Japan, the USA and Canada. The limitations that exist are that most of the studies cover only short time periods – long-term data over days, weeks and months are needed. Many studies focus on men and women in their twenties and generalise the findings, so further studies based on a larger sample, including various age groups, are required. Finally, it is necessary to comprehensively evaluate the parameters that are used as indicators of health and wellbeing, brain activity, nervous activity, endocrine activity, heart rate, sleep pattern, etc. It cannot be concluded simply that interior wood use is psychologically beneficial. The theory, methodology and practical implications of each previous study are fundamental to appreciate in this early stage of investigation. Establishing an awareness of the positive psychological, emotional and health impacts of wood products would be essential in future marketing efforts. Promoting wood products by highlighting their positive psychological associations and health-promoting effects is an excellent ambition and one to be delivered by collaborative UK strategic efforts, including research to plug gaps.

Quantification of the relationship between indoor air pollution and health is needed. This understanding needs strengthening, including key risk factors and effects of poor air quality in our homes, schools and workplaces. A coordinated effort is required among policy-making bodies to develop and apply any necessary changes.

To stay ahead, the timber industry, including sectors that are essential components of wood products (adhesives, coatings, wood preservatives, sealants, fire retardants), must continue to reduce at source emissions from products through innovation. In addition, they must progress rapidly to seek wider opportunities to:

- maximise the visual appearance of timber and wood-based products to the occupants of buildings
- retrofit timber components to impact temperature and humidity regulations
- provide design guidance for sectors to foster the application of wood and wood-based solutions.

Further investigation on the health impacts of wood in the built environment is underway to inform building, interior and product designers about wood use that is both sustainable and provides health benefits for the occupants/users. This needs to be translated into guidelines for the design of timber for healthy buildings and to support decisions about the practical value of design interventions involving elements of nature like wood.

By rethinking our built interior environment and incorporating natural materials, we can also make a positive long-term contribution towards our health and wellbeing. While we have not fully explored the potential of timber and different wood species, it is already abundantly clear that the warm, natural aesthetic of wood can provide an inviting and enriching enhancement of our everyday lives. An increasing body of research shows that being surrounded by wood at home, work or school has positive effects on the body, the brain and the environment.

The demand for healthy buildings will continue to grow, as more buildings are certified, as awareness deepens about the impact of our buildings on our health and as the commercial and societal values of healthy occupants and buildings crystallise and become part of the asset value in the future. The reasons underlying the findings reported in this publication are complex and further exploration rooted in the field of environmental psychology is warranted. However, the results could have far-reaching implications for manufacturers of wood products as architects and designers utilise wood in interiors seeking to differentiate themselves in an increasingly competitive marketplace. Specifically, these findings point to an opportunity to market wood in an entirely new and innovative manner with the inclusion of health benefits into the total product concept.

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## References

[1] Levin, H., Building ecology: an architect's perspective on healthy buildings, in M. Maroni et al., (eds) *Proceedings of Healthy Buildings '95, proceedings of the fourth international conference on healthy buildings*, Milan, Italy, September 1995.

[2] Department of Health, Health building note 00-01: *General design guidance for healthcare buildings*, 2014.

[3] Department of Education, Healthy Pupils Capital Fund, 2017.

[4] McGraw Hill Research Foundation and USGBC Centre for Green Schools, *The impact of school buildings on student health and performance*, 2012, at www.centerforgreenschools.org/impact-school-buildings-student-health-and-performance.

[5] www.bregroup.com/biophilic.

[6] BRE, *Full cost of poor housing FB 81*, ISBN 978-1848064454, BRE, 2016.

[7] CIBSE, *TM40: health issues in building services*, ISBN 978-1903287651, CIBSE, 2006.

[8] Building Regulations Part F (October 2010), supported by DfE Building Bulletin 101, *Ventilation of school buildings*, 2014, at www.gov.uk/government/publications/building-bulletin-101-ventilation-for-school-buildings.

[9] www.hok.com/thought-leadership/workplace-strategies-that-enhance-human-performance-health-and-wellness.

[10] May, N., McGilligan, C. and Ucci, M., *Health and moisture in buildings*, UKCMB, 2017.

[11] Burnard, M. and Kutnar, A., Restorative environmental design: wood as a material for sustainable, healthy environments, in *Proceedings of the 57th International Convention of Society of Wood Science and Technology* June 23–27, 2014, Zvolen, Slovakia.

[12] Derr, V. and Kellert, S. R. *Making children's environments 'R.E.D': restorative environmental design and its relationship to sustainable design*. In Pavlides E and Wells J (eds) Proceedings of the 44th annual conference of the Environmental Design Research Association. Providence, Rhode Island. May 29–June 1 2013; pp. 31–37

[13] Kutnar, A., InnoRenewCoE: wood and wood products in restorative environmental and ergonomic design (REED), 2017, at www.uef.fi/documents/1285125/1460883/AndrejaKutnar_+170425KareliaSymposium.pdf/94311cc0-2fba-439b-aef9-3be26a634a5c.

[14] Wilson, E. O., *Biophilia: the human bond with other species*, ISBN 978-0674074422, Harvard University Press, 1984.

[15] Kellert, S. R., Heerwagen, J. and Mador, M. *Biophilic design: the theory, science and practice of bringing buildings to life*, ISBN 978-0470163344, Wiley, 2008.

[16] Terrapin Bright Green, *14 patterns of biophilic design and how to apply them to improve health and wellbeing in the built environment*, 2014, at www.terrapinbrightgreen.com/report/14-patterns.

[17] Park, B.-J., Tsunetsugu, Y., Kasetani, T., Hirano, H., Kagawa, T., Sato, M. and Miyazaki, Y., Physiological effects of shinrin-yoku (taking in the atmosphere of the forest): using salivary cortisol and cerebral activity as indicators. *Journal of Physiological Anthropology* 2007; 26(2): 123–128.

[18] Song, C., Ikei, H. and Miyazaki, Y., Physiological effects of nature therapy: a review of the research in Japan. *International Journal of Environmental Research and Public Health* 2016; 13(8): 781.

[19] Wood2New, *Competitive wood-based interior materials and systems for modern wood construction*, at www.wood2new.org/wp-content/uploads/2017/02/2017-Wood2New-final-report.pdf.

[20] Wood2New, *Competitive wood-based interior materials.*

[21] helTREnkelt (Simply Wood), *Absolute passive energy design: achieving passive house level by utilizing hygrothermal properties of wood*, 2014. at www.gaiaarkitekter.no/images/gaia_lista/boker_og_artikler/pdf_artikler/Absolute_Passiv_Energy_Design_March_2015_RE.pdf.

[22] Nore, K., *Hygrothermal mass: potential improvement of indoor climate using building materials*, 2016, at www.wood2new.org/wp-content/uploads/2014/08/B2.3-Nore.pdf.

[23] Fell, D., *Wood in the human environment: restorative properties of wood in the built indoor environment*, PhD thesis, University of British Columbia, 2010.

[24] Royal College of Physicians, *Every breath we take: the lifelong impact of air pollution*, ISBN 978-1860165672, RCP, 2016.

[25] World Health Organization, Indoor air quality: organic pollutants. *Environmental Technology Letters* 1989; 10(9): 855–858.

[26] Risholm-Sundman, M., Lundgren, M., Vestin, E., et al., Emissions of acetic acid and other volatile organic compounds from different species of solid wood. *Holz als Roh-und Werkstoff* 1998; 56: 125.

[27] Soto-Garcia, L., Ashley, W.J., Bregg, S., et al., VOCs emissions from multiple wood pellet types and concentrations in indoor air. *Energy Fuels* 2015; 29(10): 6485–6493.

[28] Nyrud, A. Q., Bringslimark, T. and Englund, F. Wood use in a hospital environment: VOC emissions and air quality. *European Journal of Wood Products* 2012; 70: 541.

[29] Zylkowski, S. and Frihart, C., *Volatile organic compound emissions from engineered wood products*, Research note FPL-RN-0350, US Department of Agriculture, Forest Service, Forest Products Laboratory, 2017.

[30] Türkez, H. and Aydın, E. In vitro assessment of cytogenetic and oxidative effects of $\alpha$-pinene. *Toxicology and Industrial Health* 2016; 32(1): 168–176.

[31] Song, X., Li, H., Li, C., Xu, J. and Hu, D., Effects of VOCs from leaves of *Acer truncatum* Bunge and *Cedrus deodara* on human physiology and psychology. *Urban Forestry & Urban Greening* 2016; 19: 29–34.

[32] Won, D., Magee, R. J., Lusztyk, E., et al., A comprehensive VOC emission database for commonly-used building materials, in *Proceedings of the 7th International Conference of Healthy Buildings*, 7–11 December 2003, National Research Council of Canada, at www.researchgate.net/publication/44055681_A_Comprehensive_VOC_emission_database_for_commonly-used_building_materials.

[33] Fechter J.-O., Englund, F. and Lundin, A., Association between temperature, relative humidity and concentration of volatile organic compounds from wooden furniture in a model room. *Wood Material Science & Engineering* 2006; 1(2): 69–75.

[34] Schreiner, L., Beauchamp, J. and Buettner, A., Characterisation of odorants in wood and related products: strategies, methodologies and achievements. *Pro Ligno* 2017; 13(4): 55–62.

[35] Matsubara, E., Fukagawa, M., Okamoto, T., Ohnuki, K., Shimizu, K. and Kondo, R., The essential oil of *Abies sibirica* (Pinaceae) reduces arousal levels after visual display terminal work. *Flavour & Fragrance Journal* 2011; 26: 204–210.

[36] WPA, *Indoor Air Quality (IAQ) in homes constructed with preservative treated wood*, 2017.

[37] STI Project, *Technology for minimising the environmental impact of treated timber products*, 4/017, 2007.

[38] BS EN 15251:2007 *Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics*, BSI.

[39] ISO 17772-1:2017 *Energy performance of buildings – indoor environmental quality*, ISO.

[40] ISO 16000-9:2006 *Indoor air – Part 9: determination of the emission of volatile organic compounds from building products and furnishing – Emission test chamber method*, ISO.

[41] ISO 16000-10:2006 *Indoor air – Part 10: Determination of the emission of volatile organic compounds from building products and furnishing – Emission test cell method*, ISO.

[42] ISO 16000-6:2011 *Indoor air – Part 6: Determination of volatile organic compounds in indoor and test chamber air by active sampling on Tenax TA sorbent, thermal desorption and gas chromatography using MS or MS-FID*, ISO.

[43] ISO 7708:1995 *Air quality – Particle size fraction definitions for health-related sampling*, ISO.

[44] ISO 4224:2000 *Ambient air – Determination of carbon monoxide – non-dispersive infrared spectrometric method*, ISO.

[45] ISO 13964:1998 *Air quality – Determination of ozone in ambient air – ultraviolet photometric method*, ISO.

[46] BS EN 717-1:2004 *Wood-based panels: determination of formaldehyde release – formaldehyde emission by the chamber method*, BSI.

[47] BS EN 717-3:1996 *Wood based panels: determination of formaldehyde release by the flask method*, BSI.

[48] BS EN 13999-1:2013 *Adhesives: short term method for measuring the emission properties of low-solvent or solvent-free adhesives after application. General procedure*, BSI.

[49] BS EN 13999-4:2007+A1:2009 *Adhesives. Short term method for measuring the emission properties of low-solvent or solvent-free adhesives after application. Determination of volatile di-isocyanates*, BSI.

[50] BS EN 13986:2004. *Wood-based panels for use in construction – characteristics, evaluation of conformity and marking*, BSI.

[51] CEN/TS 16516:2013. *Construction products – assessment of release of dangerous substances – determination of emissions into indoor air*, BSI.

[52] Shabha G. (2018) How can BIM be a Catalyst for intelligent monitoring of Health Care Facilities in Britain? The Dichotomy of Digital vs Operational Model www.digitalconstructionweek.com/blog/how-can-bim-be-a-catalyst-for-intelligent-monitoring-of-health-care-facilities-in-britain-the-dichotomy-of-digital-vs-operational-model.

[53] Department for Education, *Building Bulletin 101: guidelines on ventilation, thermal comfort and indoor air quality in schools: version 1*, DfE, 2018.

[54] WGBC, *Health, wellbeing and productivity in offices: the next chapter for green building*, WGBC, 2014.

[55] WGBC, *Health, wellbeing and productivity in retail: the impact of green buildings on people and profit*, WGBC, 2016.

[56] WGBC, *Doing right by planet and people: the business case for health and wellbeing in green buildings*, WGBC, 2018.

[57] ISO 14024:2018 *Environmental labels & declarations: type I environmental labelling. Principles + procedures*, ISO.

[58] Article R221-3 of the Environment Code, Decree No. 2011-1728 of 2 December 2011 and Decree No. 2015-1000 of 17 August 2015.

[59] Kingdom of Belgium, Royal Decree establishing threshold levels for the emissions to the indoor environment from construction products for certain intended uses, at www.eco-institut.de/wp-content/uploads/2017/04/Royal_DecreeEN.doc.

[60] www.umweltbundesamt.de/en/topics/health/commissions-working-groups/committee-for-health-related-evaluation-of-building#textpart-1.

[61] www.blauer-engel.de/en.

[62] www.nordic-ecolabel.org.

[63] www.natureplus.org.

[64] https://ww2.arb.ca.gov/homepage.

[65] www.ec.europa.eu/environment/ecolabel.

[66] www.globalgreentag.com/get-certified/product-health-declaration-the-phd-tool.

[67] www.c2ccertified.org/products/registry.

[68] DCLG, The Construction Products Regulations 2013 and Approved Document 7 (2013 edition), 2013, at www.gov.uk/government/publications/the-construction-products-regulations-2013-and-approved-document-7-2013-edition.

[69] www.health.belgium.be/sites/default/files/uploads/fields/fpshealth_theme_file/19095734/KB%20Vloerbekleding.pdf.

[70] www.legifrance.gouv.fr/eli/decret/2011/3/23/DEVL1101903D/jo.

[71] www.legifrance.gouv.fr/eli/arrete/2011/4/19/DEVL1104875A/jo.

[72] www.dibt.de/de/Fachbereiche/data/II4_Anforderungen_bauliche_Anlagen_Gesundheitsschutz_Entwurf.pdf.

[73] www.emicode.com/en/emicode-r/licensable-products.

[74] www.eco-institut.de/fileadmin/contents/Nationale_Pruefzeichen/BlauerEngel/156-1102-d.pdf.

[75] www.eco-institut.de/fileadmin/contents/Nationale_Pruefzeichen/BlauerEngel/176-1301-d.pdf.

[76] Burnard, M. and Kutnar, A., Wood and human stress in the built indoor environment: a review. *Wood Science and Technology* 2015; 49(5): 969–986.

[77] Nyrud, A. Q. and Bringslimark T., Is interior wood use psychologically beneficial? A review of psychological responses toward wood. *Wood and Fiber Science* 2010; 42(2): 202–218.

[78] Knox, A., Parry-Husbands, H. and Pollinate, *Workplaces: Wellness + Wood = Productivity*, 2018, at www.makeitwood.org/documents/doc-1624-pollinate-health-report---february-2018.pdf.

[79] Jonsson, O., Lindberg, S., Roos, A., Hugosson, M. and Lindström, M., Consumer perceptions and preferences on solid wood, wood-based panels, and composites: a repertory grid study. *Wood and Fiber Science* 2008; 40(4): 663–678.

[80] Nyrud and Bringslimark, *Is interior wood use psychologically beneficial?*

[81] Lyytikäinen, P., *Puupintojen restoratiiviset ominaisuudet sisätiloissa ja aistiminen tunto- ja näköaistin avulla (Restorative abilities and haptic and visual perceptions of wooden surfaces)*, Master's thesis, University of Helsinki, Faculty of Forest Products, 2015.

[82] Planet Ark, *Wood housing health humanity report*, 2015, at www.makeitwood.org/documents/doc-1253-wood--housing--health--humanity-report-2015-03-00-final.pdf.

[83] Planet Ark, *Wood nature inspired design: an update of the Wood: housing, health, humanity report*, 2016, at www.makeitwood.org/documents/doc-1501-wood---nature-inspired-design-report-final.pdf.

[84] Jiménez, P., Dunkl, A., Eibel, K., et al., Wood or laminate? Psychological research of customer expectations. *Forests* 2016; 7(11): 275.

[85] Ball, R. D., Killerby, S. K. and Ridoutt, B. G., First impressions of organisations and the qualities connoted by wood in interior design. *Forest Products Journal* 2002; 52(10): 30–36.

[86] www.wood2new.org.

[87] Nyrud, A. Q., Bringslimark, T. and Bysheim, K., Benefits from wood interior in a hospital room: a preference study. *Architectural Science Review* 2014; 57(2): 125–131, at www.westernforesteconomists.org/wp-content/uploads/2014/12/Nyrud-et.al_.-Health-benefits-from-wood-interiors-in-hospitals.pdf.

[88] Strobel, K., Nyrud, A. Q. and Bysheim, K., Interior wood use: linking user perceptions to physical properties. *Scandinavian Journal of Forest Research* 2017; 32(8): 798–806.

[89] Tsunetsugu, Y., Miyazaki, Y. and Sato, H., Visual effects of interior design in actual-size living rooms on physiological responses. *Building and Environment* 2005; 40(10): 1341–1346.

[90] Matsubara, E. and Kawai, S., VOCs emitted from Japanese cedar (*Cryptomeria japonica*) interior walls induce physiological relaxation. *Building and Environment* 2014; 72: 125–130.

[91] Sakuragawa, S., Change in the impression of rooms with interior wood finishes arranged differently: questionnaire survey with the use of photographs for the analysis of impressions of rooms concerning living activities. *Journal of Wood Science* 2006; 52(4): 290–294.

[92] Nyrud et al. *Benefits from wood interior in a hospital room*.

[93] Kelz, C., Grote, V. and Moser, M. *Interior wood use in classrooms reduces pupils' stress levels*, 2011, at www.proceedings.envpsych2011.eu/files/doc/342.pdf.

[94] www.holzfachberater.at/seiten/news.php?m=12&id=2.

[95] Pervanidou, P. and Chrousos, G.P., Metabolic consequences of stress during childhood and adolescence. *Metabolism: Clinical & Experimental* 2012; 61(5): 611–619, at www.metabolismjournal.com/article/S0026-0495(11)00344-1/fulltext.

[96] Anme, T., Watanabe, T., Tokutake, K., et al., Behavior changes in older persons caused by using wood products in assisted living. *Public Health Research* 2012; 2(4): 106–109.

[97] Rice, J., Kozak, R., Meitner, M. J. and Cohen, D. H., Appearance of wood products and psychological well-being. *Wood and Fiber Science* 2006; 38(4): 644–659.

[98] Augustin, S. and Fell, D., *Wood as a restorative material in healthcare environments*, version 1.2, FP Innovations, 2015, at www.ekkist.co/wp-content/uploads/2018/05/Wood-as-a-Restorative-Material-in-Healthcare-Environments.pdf.

[99] Fell, D., *Wood and health in the built environment*, University of British Columbia, 2010, at www.open.library.ubc.ca/clRcle/collections/ubctheses/24/items/1.0071305.

[100] Stephen, F., Health benefits of wood, plants and nature in the human environment: an analysis of the past 15 years of research and its application potential. *Open Access FRST* 2011; 497, at www.open.library.ubc.ca/clRcle/collections/undergraduateresearch/52966/items/1.0075512.

[101] Fell, D., *Consumer visual evaluation of Canadian wood species*, FPInnovations, 2002.

[102] Ridoutt, B. G, Ball, R. D. and Killerby, S. K., Wood in the interior office environment: effects on interpersonal perception. *Forest Products Journal* 2002; 52(9): 23–30.

[103] Fell, D. *Wood and human health*, FPInnovations, 2011, at www.solutionsforwood.com/_docs/reports/Wood_Human_Health_final-single.pdf.

[104] Knoll Inc., *Benefits of wood*, Knoll Inc., 2014, at www.knoll.com/document/1353003671877/Benefits-of-Wood-Knoll_wp.pdf.

[105] www.thinkwood.com/news/office-spaces.

[106] Planet Ark, *Wood housing health humanity report*.

[107] www.architizer.com/projects/timber-dentistry.

[108] www.holzfachberater.at/seiten/news.php?m=12&id=2.

[109] www.architizer.com/projects/osteopathie-praktijk-roosendaal.

[110] *Wood in healthcare: a natural choice for enhancing human wellbeing, naturally:wood – British Colombia Wood*, 2012, at www.structurlam.com/wp-content/uploads/2016/12/Wood-in-Healthcare-Case-Study.pdf.

[111] www.architizer.com/projects/knowledge-centre-st-olavs-hospital

[112] www.architizer.com/projects/livsrum-cancer-counselling-center.

[113] . www.architizer.com/projects/heathcare-center-for-cancer-patients.

[114] www.architizer.com/projects/skandion-clinic.

[115] www.woodarchitecture.fi/articles/positive-health-effects-wood-building-material.

[116] www.woodworks.org/wp-content/uploads/Herrington.pdf.

[117] www.thinkwood.com/news/office-spaces.

[118] www.architizer.com/projects/medical-care-center-limay.

[119] www.woodforgood.com/why-choose-wood/health-and-wellbeing.

[120] www.barbourproductsearch.info/can-timber-construction-benefit-health-and-blog000407.html#.

[121] www.architizer.com/blog/inspiration/collections/wooden-healthcare-facilities.

[122] www.wood-protection.org/files/7514/8120/0685/WPA_Manual_Industrial_Wood_Preservation_E2_April_2012.pdf.

[123] EN BS 8417:2011+A1:2014 *Preservation of wood. Code of practice*, BSI.

[124] www.wood-protection.org/files/9915/3596/8906/WPA_FRT_Manual_E4_Oct_2018.pdf.

[125] Perkins C. (2017) *Healthy Homes indoor air quality and materials selection,* Arup UKGBC Technical Paper, March 2017. www.ukgbc.org/sites/default/files/08490%20UKGBC%20-%20ARUP%20Materials%20Paper%20FINAL.PDF

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