ASSOCIATION BETWEEN WOODEN BUILDINGS, HEALTH AND INDOOR AIR CLIMATE

– A REVIEW OF THE LITERATURE

December 2020

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Dansk konklusion

Formålet med denne litteratur gennemgang var at opsummere eksisterende viden om sammenhængen mellem træbyggeri, sundhed og indeklima. Litteratursøgningen resulterede i få studier, der undersøgte sammenhængen mellem træbyggeri og sundheds effekter. Søgningen resulterede dog i en omfattende litteratur om forurenende stoffer og indeklima i træbyggerier. Denne viden blev således opsummeret og medtaget i rapporten. Det skal dog bemærkes, at konklusionerne om indendørs miljøforhold i træbygninger ikke afspejler en systematisk gennemgang af den eksisterende litteratur om indeklima i trækonstruktioner, idet vi har inddraget yderligere litteratur på området.

Studierne, inkluderet i denne rapport, var oftest udført på enfamiliehuse. De undersøgte bygninger i studierne inkluderede forskellige former for trækonstruktioner – træramme konstruktioner eller bjælkehuse med varierende mængder af træ i det indre miljø. Der blev i studierne ikke skelnet tydeligt mellem forskellige typer, hvorfor vi ikke har været i stand til at identificere forskelle inden for undertyper af trækonstruktioner.

Sammenfattende indikerer den eksisterende viden modstridende resultater for sammenhængen mellem træbyggeri og sundhed. På grund af den sparsomme litteratur, heterogenitet og risiko for bias i studierne, kan der ikke drages klare konklusioner om sammenhængen. Imidlertid fandt ingen af de inkluderede undersøgelser en sammenhæng mellem at bo i træhuse og bygningsrelaterede symptomer.

Træbyggeri og byggematerialer synes at være relateret til tilfredshed, opfattelse og komfort på en kompleks måde. Ift. det termiske miljø viste studierne risiko for overophedning i varmt klima og træk under kolde forhold i trækonstruktioner. Imidlertid kan træets hygroskopiske kapacitet reducere variationerne i fugtighed og derved forbedre komforten i træbygninger. Etagestøj er stærkt påvirket af konstruktionen, gulvmaterialerne og nærheden til andre og således en bekymring i lette træbygninger. Lugt fra træmaterialer påvirker ikke selve komforten, men undersøgelser viste, at muglugt er forbundet med nedbrydningsprodukter fra chlorphenoler i træbeskyttelsesmidler.

Nogle undersøgelser fandt forhøjede VOC-koncentrationer i indeklimaet i træbygninger sammenlignet med gennemsnitsværdier eller andre konstruktions typer. Især niveauer for terpener, carbonyler (f.eks. Fra OSB) og muligvis myresyre, eddikesyre og acetaldehyd kan være forhøjet i træbygninger. Dette bør dog bekræftes i fremtidige studier. Den samlede litteratur viser, at andre faktorer som alder, materialetype, årstid, ventilation, fugtindhold, opvarmningstype og ozonkoncentration, kan have en væsentlig indvirkning på emissionskoncentrationer i træbygninger. Derudover er VOC-koncentrationer stærkt afhængige af materialernes placering i bygningen og af emissionerne fra andre overfladematerialer, såsom OSB i byggeri og møbler. Formaldehyd har været forbundet med øget sensorisk irritation, risiko for astma, allergi og kræft. Baseret på de inkluderede undersøgelser kan der imidlertid ikke drages nogen konkret konklusion om sundhedseffekter relateret til formaldehydeksponering i trækonstruktioner.

Denne gennemgang viser, at der mangler viden om helbredseffekter relateret til træbyggeri. Dette skyldes blandt andet heterogenitet i design, mål for eksponering og helbredsudfald i de gennemførte studier. Der er således behov for epidemiologiske opfølgningsstudier med objektive mål for helbredsudfald. Særligt er der behov for undersøgelser af perioden fra byggeriets afslutning og gennem de første års anvendelse. Vi fandt ingen undersøgelser af effekterne af bygninger og materialer fra fleretagers træbyggeri. Derfor er der et presserende behov for at undersøge indeklimaet i moderne højhuse i træ. Desuden er der brug for en bedre definition af "træbyggeri" for at muliggøre sammenligning at resultater på tværs af bygningstyper, dvs. klassificering af "Bjælke hus", "Tung træramme" og "Let træramme".

Introduction

According to WHO, people in Europe spend approximately 90% of their time indoors (WHO, 2013), which makes indoor environments crucial for our health and well-being. Wooden buildings have always been attractive to a portion of population. During recent years wood construction has entered the mainstream and has also been introduced as a concept for multifamily housing. This may be due to an increasing awareness of the environmental costs and demand to move towards sustainability in construction, combined with a growing trend to bring nature into the indoor environment (Lowe, 2020; Winchester & Reilly, 2020).

Environmental benefits have been advocated as an advantage of wood use in the construction sector. Wood is a renewable material, can store carbon in the structure for decades and the production of wooden building materials is less CO_2 intensive compared to the production of traditional building materials such as steel and concrete (Alapieti et al., 2020; Hafner & Rüter, 2018; Heräjärvi, 2019; Jensen & Craig, 2019; Winchester & Reilly, 2020).

Wood is also promoted as a material that increases the sense of the presence of nature indoors and thereby increases the comfort and well-being of occupants. "Green building", "Nature connected design" and "Biophilic design" are all terms referring to interior designs that, use natural materials, shapes, forms and colors to give a feeling of being connected with nature (Alapieti et al., 2020; ARK; Augustin & Fell, 2015; Burnard & Kutnar, 2015; Lowe, 2020).

On the other hand, wood is a source of emissions of e.g. volatile organic compounds (VOCs) such as aldehydes (incl. formaldehyde), terpenes, organic acids (Nore et al., 2017; Salthammer & Bahadir, 2009; Salthammer et al., 2010), and thus may pose a concern regarding adverse health effects. Numerous studies on emissions from various building materials have been conducted, but the amount of emissions from wood differ between materials and according to the manufacturing process. The additives (adhesives, coatings and preservatives) being used, temperature, humidity, light, air exchange, age of the material and occupant behavior further complicate the comparison of materials and the study of their effects on human health, perception and wellbeing in these buildings (Pibiri et al., 2020; Salthammer & Bahadir, 2009; Salthammer et al., 2010; Weigl et al., 2009; WHO, 2013). Wooden buildings are also relatively unique in terms of their thermal properties, impact on light and noise conditions.

To the best of our knowledge the associations between wooden buildings, health and these various elements of indoor climate is still limited. This literature review aims to summarize the evidence of associations between wooden buildings, indoor climate and occupant health and wellbeing.

Method

Between 30.05.2020 and 09.06.2020 a systematic literature search was conducted through scientific databases (Pubmed, Embase and Scopus) using search terms on wood construction and outcomes related to health and indoor air. The search terms and strategies are presented in Appendix A. Conference proceedings from The International Society of Indoor Air Quality and Climate since 2005 and Google Scholar were also used. For each conference the titles (and abstracts where these were available in the conference program) were searched for the terms: "wood" OR "timber" OR "log-" OR "log". Titles and abstracts were reviewed to ensure that each item matched the inclusion criterion.

Criterion for the studies to be included in this review were the following: i) the study occurred in wooden buildings or wooden construction, and ii) it included direct measurement of physical or mental health, or comfort indicators.

Studies measuring emissions from single materials (e.g. furniture, wall covering, ceiling and floor), studies on different adhesives, finishing and preservatives and on structural issues (wind, stability) as well as studies conducted in test chambers were only included when deemed substantially important in the context in which we look at wooden buildings (not its specific elements). See next section for full inclusion criteria.

We would have liked to classify the different types of wooden constructions into categories i.e.: ”log” “medium frame” and ”light frame”. However, there is no clear definition widely accepted in the literature and thus this review uses the terms being used in the referred studies.

Results

Literature search

The literature on associations between wooden buildings and health or comfort is limited (Figure 1). Only 36 studies met the inclusion criterion. Most studies in wooden buildings measured physiological parameters associated with indoor air quality. Studies on human health and comfort were predominantly performed in simulated environments, and they focused on effects of single elements related to the interior environment (e.g. wall covering, furniture etc.). Because of the limited literature, this review was extended to include literature on emissions and indoor air quality in wooden building and their possible health effects. Hence, 55 studies on emissions and indoor air quality found through the systematic search, references and from the reviewing process were included.

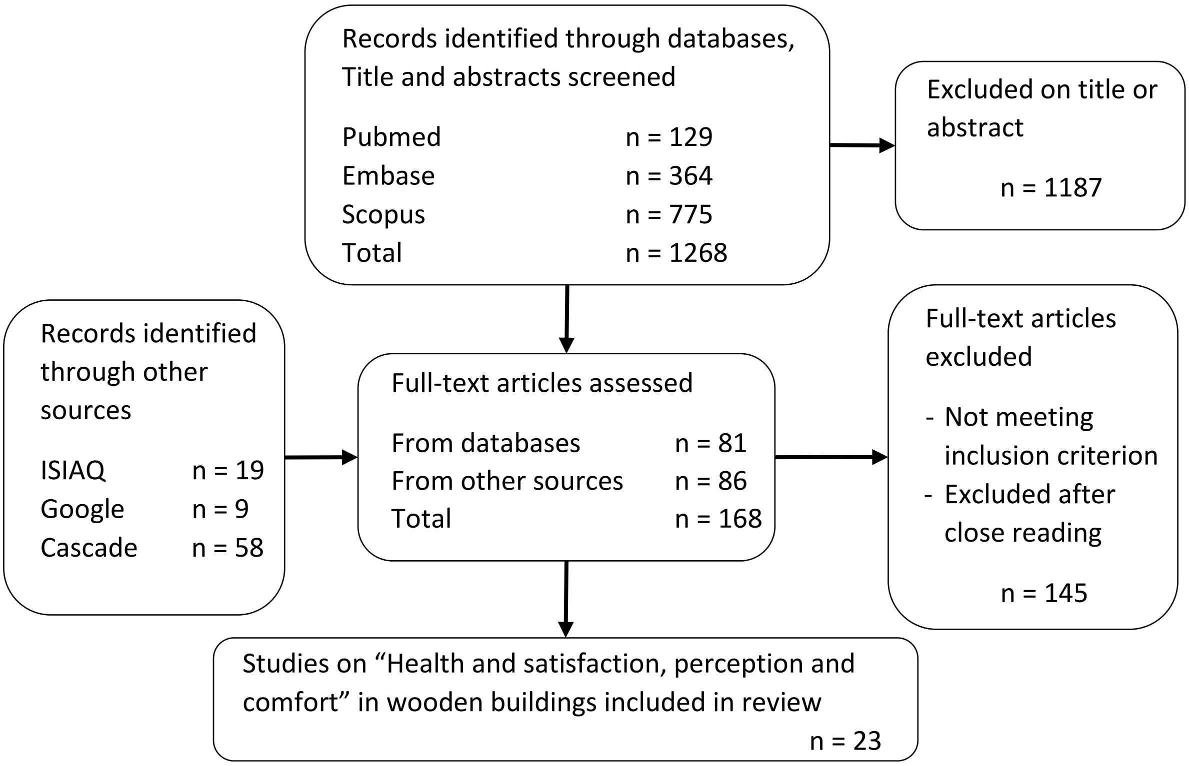

FIGURE 1: FLOWCHART OF LITERATURE SEARCH ON WOODEN CONSTRUCTION AND HEALTH

Emissions and indoor air quality in wooden buildings

VOCs

Terpenes and carbonyl VOCs are the most commonly identified and quantified species in wood-based constructions (Harb, 2018). In a Swedish study conducted on a large wooden building, total volatile organic compound (TVOC; see ISO 16000-6) levels did not exceed the then recommended guideline value of 300 µg/m^3. (Newer approaches to TVOC regulation have been proposed (e.g. (Fromme et al., 2019). Terpenes were the dominant VOC in indoor air. Simulated ozone episodes affected the indoor air quality through ozone initiated indoor air chemistry of the terpenes. The results demonstrate that terpene emissions in locations with elevated ozone concentrations may lead to undesired reaction products in wooden buildings (Langer et al., 2011). Although, higher concentrations of aliphatic aldehydes and bicyclic terpenes are anticipated in buildings with large amounts of timber, low emission timber buildings can be constructed if the building materials are selected carefully. Indeed, Winther & Clorius (2002) reported concentration of aldehydes and terpenes below threshold values suggested in 1996 by the Nordic Committee on Building Regulations (Nielsen et al., 1996) in a single-family house constructed with large exposed glued solid wood elements on inner surfaces.

In a Hungarian low-energy wooden house, the concentration of the detected TVOC was similar to average values in Europe (Patkó et al., 2013). TVOC from artificial building materials (particleboard (PB), medium density fiberboard (MDF), plywood of Radiata Pine (PRP), and plywood of Oceania Timber (POT)) showed lower levels of emissions than natural lumbers in the order MDF > PRP > PB > POT. The TVOC emissions from lumbers were approximately 1.3–47.6 times higher than those of artificial building materials (Son et al., 2013).

Compared to standard French houses, Derbez et al. reported that the concentrations of benzene, ethylbenzene, m- and p-xylenes, $PM_{2.5}$ and radon were low in seven newly built energy-efficient houses of which six were with wooden frame (Derbez et al., 2014). Four of the buildings had cellulose/wood fiber as insulation material. In contrast, the levels of acetaldehyde, hexanal, n-decane, n-undecane, o-xylene and styrene were higher in these new homes. In another study on similar French houses (although not all wooden), higher concentrations of terpenes, that is, α-pinene and limonene, and hexanal were found compared to previous studies (Derbez et al., 2018). α-pinene and hexanal are emitted by wood or wood-based products used for the construction, insulation, decoration, and furnishings of the dwellings. Due to potentially elevated concentrations of terpenes and aldehydes in wooden buildings, indoor chemistry may differ in these buildings from traditional non-wood constructions and may lead to different chemical composition of air and subsequent exposure, especially in the presence of ozone and nitrogen dioxide (Fischer et al., 2013).

Common VOC emissions in buildings with wooden constructions can be lower than in other types of buildings. Formaldehyde concentrations were significantly higher in modern non-wood (stone or concrete) houses than in wooden houses in Nagoya (Sakai et al., 2004). They were generally higher in newer buildings, possibly due to less natural ventilation and more emission sources in modern buildings. Concrete buildings had also higher NO_2 levels, which may indicate differences in ventilation and other sources unrelated to the type of construction. VOC levels in new Japanese homes were shown to decrease after about 1 year. However, formaldehyde and α-pinene related to wooden materials may need a longer time than the other compounds (Park & Ikeda, 2006). Concentrations of benzene, toluene, p-dichlorobenzene, o-, m-, p-xylene can be also shown to be high in Japanese wooden houses, especially in newly constructed ones. Higher air leakage and increasing age lead to lower concentrations (Sakaguchi & Akabayashi, 2003). Čech et al. (2016) characterized the emissions of VOCs in the indoor air of wood-based buildings (timber frame family house, office, log cabin, and log house) in relation to season, age of the building, air moisture content and composition of building materials. The concentrations of VOCs in the indoor air of these wood-based buildings were influenced by air moisture content, measurement season, age of the building, material composition of walls, furnishings and type of heating. The highest concentrations of monitored VOC were measured in the log house. However, this was attributed to the fact that a tile stove was situated directly in the monitored room.

The presence of the same chemical compounds in the air sampled from inside a building construction and in room air could indicate that the structure acts as source, but common indoor chemicals may have other sources indoors as well (Glader & Liljelind, 2011). Source apportionment of VOC concentrations in three newly built timber frame houses revealed that the apportionment of VOC source contributions is dependent on the position of source materials in the building (surface materials or internal materials) and the ventilation conditions (Plaisance et al., 2017). The concentrations of compounds after the shutdown of the ventilation system did not increase in equivalent proportion. The contribution of indoor surface materials like the door material and furniture explained over 65% of total VOCs. While the increase in formaldehyde concentration is mainly due to furniture (contribution of 70%), the increase in α-pinene concentration was almost exclusively attributable to the emission of door material (up to 84%).

Acids, alcohols, aldehydes, furans, ketones, polycyclic aromatic hydrocarbons (PAH), phenols and terpenes, were more associated with moisture damaged wooden buildings than undamaged ones (Glader & Liljelind, 2009). Buildings constructed using prefabricated systems such as wooden buildings, used to be traditionally sensitive to air leakage and moisture movement particularly in their construction joints. Air movement occurs mostly in the construction joints relative to the clear (joint free) wall sections (Asiz et al., 2008). This may well be less of a problem in modern wood-based prefabricated homes.

Decomposition of wooden building materials may also act as a major source for acetic acid, formic acid, acetaldehyde and methanol (Liu et al., 2019; Maraun et al., 2016; Pibiri et al., 2020; Salthammer, 2020). Acetic acid, formic acid and methanol together accounted for ~75% of the total continuous indoor emissions of high-baseline species in a wooden framed US residence (Liu et al., 2019). Worthy of note is also the contribution of construction processes to VOC concentrations. Plaisance (2017) carried out field measurements at six construction stages in three energy-efficient timber-frame houses. Here m/p-xylenes and ethylbenzene concentrations ranged from 1900 to 5100 $\mu g/m^3$ occurring at the time of the structural work (representing more than 88% of the sum of the target VOCs). This pollution was due to the emissions from the polyurethane adhesive mastic used as a sealing material. The superposition of materials led to a slowing down of the VOC emission process from polyurethane adhesive mastic, which explains the slow concentration decay recorded in houses during the construction process. At the final construction stage, the concentration levels were low for all compounds, with aldehydes (formaldehyde, acetaldehyde and hexanal) now becoming the major components (representing 50–70% of the sum of the target VOCs). This is in agreement with the fact that the sources of aldehydes are the most numerous among the materials and have rather slow emission decay kinetics.

Formaldehyde was not elevated in modern timber construction investigated by Ostendorp and Heinzow (2015). Similarly, formaldehyde levels were not significantly different in seven newly built energy-efficient houses with wood frame, compared to standard French houses (Derbez et al., 2014).

In an office building constructed using mass timber elements such as cross-laminated timber (CLT) floor and roof panels, as well as glue-laminated timber (GLT) beams and columns, formaldehyde levels were below most recommended exposure limits (Stenson et al., 2019). In a single-family house constructed with large exposed glued solid wood elements on inner surfaces, concentrations of formaldehyde were well below the WHO guideline value of 0.1 mg/m^3 (Winther & Clorius, 2002).

Salthammer et al (2010) reported 367 formaldehyde measurements performed in new prefabricated houses between 1996 and 2006. This type of housing is commonly made with wood based materials such as particle board and oriented strand board (OSB). The median concentration was 0.04 ppm (0.049 mg/m^3; conversion rate at 25 °C), and the German guideline value of 0.1 ppm (0.12 mg/m^3) was exceeded by 14% of the data (Salthammer et al., 2010). More recently, however, formaldehyde concentrations were measured in 60 German prefabricated houses between 2014 and 2016. The median value was 38 $\mu g/m^3$ (31 ppb). Uncomfortable conditions (high temperatures and high humidity) did not necessarily lead to increased formaldehyde concentrations. In comparison with the earlier measurement campaign (1996 and 2006), the concentrations from 2014 to 2016 were significantly lower (Salthammer, 2019).

Temporary Housing Units (THU)

THU (disaster shelters, refugee homes, mobile homes), which are mostly made of wood-based products, constitute a unique type of construction. Early measurements in THUs indicated substantially elevated VOC concentrations. Formaldehyde concentrations above 0.1 ppm were measured in 147 of the 470 mobile homes manufactured between 1966 and 1984 investigated by Sexton et al. (1989), and concentrations as high as 2.8 ppm have been reported (Hanrahan et al., 1985; Sexton et al., 1989). Mobile homes can also manifest high formaldehyde levels, although differences can be substantial between occupied and unoccupied mobile homes (Dingle et al., 2000).

More recently, in THU belonging to the U.S. Federal Emergency Management Administration (FEMA), contaminants present at the highest concentrations included formaldehyde, acetic acid, and 2,2,4-trimethyl-1,3-pentanediol diisobutyrate (TXIB) with median concentrations of 440 ppb (541 $\mu g/m^3$), 425 ppb, and 36 ppb, respectively (Maddalena et al., 2009). A number of VOCs had higher concentrations than published concentrations in other dwellings, but THU emission factors for most chemicals were either lower than or similar to values reported for newly constructed homes. The extensive use of composite wood products, sealants, and vinyl coverings, combined with the low air change rates relative to material surface areas, may explain the high concentrations of some VOCs and formaldehyde. It is also worth noting, that these THUs were measured in the warm and humid climate of Mississippi. Using material loading factors and ventilation rates that are relevant to the trailers, all tested material types emitted at least two chemicals (formaldehyde and nonanal) with derived concentrations in excess of chronic reference exposure levels or odor thresholds (Maddalena et al., 2009). In a similar study, formaldehyde levels among trailers ranged from 3 ppb to 590 ppb (3.7 to 726 $\mu g/m^3$), with a geometric mean of 77 ppb (95 $\mu g/m^3$). There were statistically significant differences in formaldehyde levels between trailer types. The geometric mean formaldehyde level was 81 ppb (100 $\mu g/m^3$) among travel trailers, 57 ppb (70 $\mu g/m^3$) among mobile homes, and 44 ppb

(54 µg/m³) among park models. Among travel trailers, formaldehyde levels varied significantly by brand. While formaldehyde levels varied by trailer type, all types tested had some levels ≥ 100 ppb (123 µg/m³) (Murphy et al., 2013). Moreover, increases in temperature or humidity contribute to an increase in emission factors (Parthasarathy et al., 2011).

Shinohara et al. (2014) investigated the thermal conditions and indoor concentrations of aldehydes, VOCs, and NO_2 in 19 occupied temporary houses in Fukushima, Japan. Thermal conditions in temporary log houses in the summer were more comfortable than those in pre-fabricated houses. In the winter, the indoor temperature was uncomfortably low in all of the houses, particularly the temporary log houses. Indoor air concentrations for most aldehydes and VOCs were much lower than the indoor guidelines of the Japanese Ministry of Health, Labor, and Welfare, except for those of p-dichlorobenzene, acetaldehyde, and total VOCs. Indoor acetaldehyde concentrations exceeded the guideline values in about half of the temporary houses, likely originating from the wooden building materials. Elevated NO_2 levels were associated with the use of combustion heating appliances. Log-house-type temporary houses were found to be comfortable in terms of humidity, dew condensation, and fungi based on the results of questionnaires and measurements, whereas pre-fabricated temporary houses were more comfortable in terms of temperature. In the summer, log-house-type temporary houses were comfortable in terms of temperature and humidity.

Odor

In the Chinese study comparing a steel/concrete constructed room (basic room) with three rooms with wooden construction, higher odor sensation was observed in the wooden rooms than in the basic room. Odor comfort was slightly, but not significantly higher in wooden rooms (Zhang et al., 2016).

Chloroanisoles formed by microbial degradation of chlorophenols in wood preservatives have been associated with musty malodor in frame-houses and wooden building materials (Gunschera et al., 2004; Lorentzen et al., 2016). The malodor may contribute to stress-related and inflammatory symptoms and thereby cause adverse health effects (Gunschera et al., 2004; Lorentzen et al., 2016). However, building occupants' adaptation towards odors tends to be rapid.

Thermal environment

The lack of thermal mass along with the low thermal transmittance (U-value) can be a risk factor for overheating in timber houses. Comparing the thermal environment in wooden buildings with that in buildings built with heavyweight materials, high temperatures were more frequently observed in prefabricated timber buildings. The risk of overheating was present even in mild summer weather conditions (Adekunle & Nikolopoulou, 2016; Ozoliņš et al., 2015). However, the occupants are likely not prone to extreme summertime overheating and heat stress under moderate weather conditions (Adekunle, 2019). Prefabricated timber buildings perform better in winter than summer and it was suggested that occupants are likely thermally comfortable in winter (Adekunle & Nikolopoulou, 2019, 2020). However, Derbez et al. found that the thermal comfort ranged between "rather satisfactory" and "satisfactory" in summer and between "somewhat dissatisfied" and "satisfactory" in winter in seven energy-efficient houses in France (6 of them with timber construction) (Derbez et al., 2014).

In apartments in wooden historical buildings in Estonia, the indoor temperature was outside the target value in 83% of the apartments in winter (18–25 °C) and in 25% of the apartments in summer (22–27 °C) (Arumägi et al., 2015). Complaints about unstable temperature occurred when the diurnal variations in temperature was 3.8 °C in wintertime and was correlated with complaints about cold feet. Buildings with complaints from occupants were leakier, and the air change rates and energy consumption were higher compared to buildings with no occupant complaints (Arumägi et al., 2015).

In a Finnish study, occupants in log-frame houses reported draught during winter (10.8%) more often than occupants living in light-frame houses (3.3%) and masonry/concrete houses (6.1%). None of the log-frame houses was reported to be too cold or too warm during winter (Anttila et al., 2012).

Passive solutions have been suggested to minimize summer discomfort in warm climate (Boulet & Armand-Decker, 2012). Compared to masonry constructions, wooden houses have a much lower ability to absorb water in their structures (Gunnarsen et al., 2009). On the other hand, the ability of timber to store moisture during indoor load periods and to release it back into the indoor air during unoccupied periods reduces indoor relative humidity variations. The hygroscopic capacity of timber (lower maximum relative humidity, increased humidity in winter when indoor air is often too dry) can thus improve the indoor conditions in log houses, including thermal comfort, and possibly perceived air quality (Ojanen, 2016; Simonson et al., 2001, 2002). Such passive methods of controlling the indoor climate are more successful in moderate climates than in hot and humid climates.

Noise

The literature indicates that impact noise (structure-borne sound upon an impact of an object, e.g. footsteps on a floor) may be the major cause of discomfort in wooden buildings. This is often caused by the low mass of construction (Caniato et al., 2017; Liebl et al., 2014). With proper floor construction, the flanking transmission (sound that transmits between spaces indirectly, going around, rather than directly through the main separating element, causing transmission between spaces otherwise acoustically insulated) is of minor importance. Impact sound insulation in the low frequency range is a crucial point concerning satisfaction of residents in lightweight wooden-based buildings (Bartlome & Liebl, 2014; Caniato et al., 2017). Bard et al. reported certain noise sources to be dominant within living environments of wooden buildings. Impact noise from neighbors was the most important, although installation noise from inside the building and outdoor low-frequency noise can be also disturbing. However, the overall level of acoustic comfort in contemporary wooden buildings was found to be satisfactory (Bard et al., 2019). Floor vibration was observed to be below recognized human comfort thresholds (Stenson et al., 2019). Späh et al. also found high overall ratings of acoustic satisfaction by residents in wooden buildings. Again, walking noise caused by neighbors was the most frequent complaint compared to other noise sources (Späh et al., 2014). However, building and floor construction types differ with regard to perceived acoustic annoyance caused by walking noise (Caniato et al., 2017; Olsson et al., 2012). For example, ratings of residents in single-family houses can differ from ratings of residents in multi-family houses (Späh et al., 2014). Moreover, the effects of floor finishing materials and room plans on the performance of sound insulation should be considered (Tanaka et al., 2009; Van Damme et al., 2007).

It should be noted that standards and guidelines on the acoustic indoor environment in wooden buildings may change quickly, possibly leading to the application of new construction techniques or technological solutions for timber frame constructions in order to attain the new acoustic criteria.

Light

In an experimental study, participants in a room with light brown wooden walls and a room with dark brown wooden walls scored the lighting sensation more bright and the color sensation warmer than in a basic room with painted white walls (Zhang et al., 2016). In contrast to this, a Finnish report found problems with natural light more common in log-houses than in light-frame houses and masonry/concrete houses (Anttila et al., 2012).

Health and satisfaction, perception and comfort in wooden buildings

Possible health effects of emissions

Health effects of formaldehyde

In a comprehensive review on formaldehyde in the indoor environment Salthammer et al (2010) summarized human health effects of formaldehyde exposure. Short-term exposure to formaldehyde in air concentrations ranging from 0.5 mg/m^3 (0.4 ppm) to 3.7 mg/m^3 (3.0 ppm) are associated with reversible eye, nose, nasal epithelium, and throat irritation, but not consistently with pulmonary function (Kotzias et al., 2005).

Sensory irritation is found to be the most sensitive parameter after exposure to formaldehyde, but the threshold for irritations is ambiguous (0.1 mg/m^3 (0.08 ppm) - 0.33 mg/m^3 (0.26 ppm)) (Salthammer et al., 2010). According to the risk assement, there is no clear causal association between residential formaldehyde levels below 1mg/m^3 (0.81 ppm) and asthma, respiratory sensitization or airway irritation (Umweltbundesamtes, 2016). Prolonged exposure to levels not causing sensory irritations after acute exposure is not anticipated to result in adverse health effects (Salthammer et al., 2010).
However, exposure to formaldehyde between 0.12 ppm (0.15 mg/m^3))-1.6 ppm (1.9 mg/m^3) was associated with symptoms such as eye and throat irritation, headache and fatigue among workers in mobile trailers used as temporary offices during a 34-month period (Main & Hogan, 1983). Formaldehyde has been evaluated as a major concern when it comes to environmental agents causing cancer (Irigaray et al., 2007). According to the review by Salthammer et al (2010), the classification of formaldehyde as a human carcinogen by IARC is based on work-related exposure and risk of nasopharyngeal cancer and leukemia, which has been questioned by others. No clear association has been established between the risk of leukemia and formaldehyde exposure. In 2000 the German Committee for the determination of occupational exposure limits (MAK) concluded that, at low exposure, concentrations without an increase of cell proliferation genotoxicity "play no or at most a minor role. Hence, no significant contribution to human cancer risk is expected". Accordingly, the highest concentrations not causing irritation in vivo or in vitro with an increased cell proliferation would represent a threshold for carcinogenic action upon the cells under study. A carcinogenic action is not to be expected so long as sensory irritation is avoided. This sensory irritation is the decisive end point for almost all indoor air limits proposed by regulatory bodies, and these limits should therefore provide protection against tumor induction by formaldehyde (Salthammer et al., 2010). This is supported by a recent review by Nielsen et al. (2017).

A meta-analysis of 13 observational studies associated exposure to formaldehyde in the indoor environment (homes, schools and factories) with increased risk of asthma in children and adults, despite heterogeneity in included studies (Yu et al., 2020). A dose-response relationship between higher bedroom levels of formaldehyde (mainly from glued wood products) and allergy in children was shown by Garrett et al. (1999). This study also found an association between mean respiratory symptoms and formaldehyde levels. However, associations between formaldehyde levels and any respiratory symptoms or asthma were not statistically significant.

In a study of 13 different houses 6 solid wood, 6 wood frame and 1 concrete house Fürhapper et al. (2020) showed the decay of VOC and formaldehyde until the values stabilized on the lowest level. This happened over the first 14 months for solid wood, the first 8 months for wood frame and 7 months for concrete. See Figure 2. As seen in the figures the formaldehyde concentration stayed below 60 µg/m^3 (49 ppb) for the entire period a little higher for the solid wood houses compared to the other two construction types. For VOC's there was an initial higher concentration in the wooden houses compared to the concrete house. The residents were followed for symptoms, lung function, blood pressure and eye blinking frequency over the first 7 months. According to the paper no changes were seen over time in any of the persons.

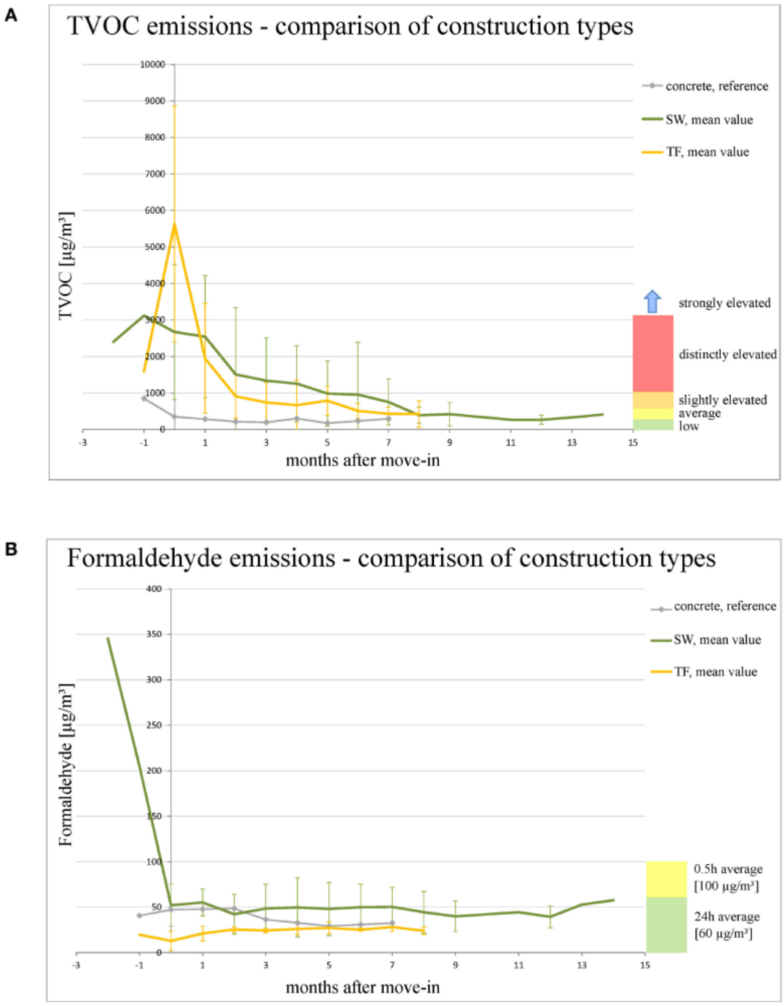

FIGURE 2: LONG-TERM PROGRESSION OF TVOC (A) AND FORMALDEHYDE (B) EMISSIONS – COMPARISON OF CONSTRUCTION TYPES.

Health effects of pinewood products

In human exposure studies, Gminski et al. found no association between 2 hours exposure to emissions from pinewood panels and sensory irritation of eyes, nose and throat, lung function, exhaled nitrogen oxide concentration or eye blink frequency (Gminski et al., 2011b) or between 2 hours exposure to emissions from oriented strand boards and sensory irritations and pulmonary effects (Gminski et al., 2011a). Nor did Skulberg et al. (2019) find differences in irritation and general symptoms between low TVOC loads from Norway spruce (Picea abies) and TVOC loads from Scots pine (Pinus sylvestris); loads for both species were higher than international standards in a 2-hour experimental study.

Health related to wooden buildings

In a Finnish study with 729 participants, occupants in log-frame houses (n = 37) self-reported their general health as "good" more often than occupants living in light-frame (n = 609) or masonry/concrete houses (n = 83), but after adjustment for potential confounders the associations were not statistically significant (light frame odds ratio (OR): 0.55 (0.25; 1.20), masonry/concrete OR: 0.64 (0.25; 1.62)) (Anttila et al., 2012).

Takeoka et al. investigated associations between several home environmental factors, including living in a wooden house, and self-reported health outcomes among 1048 Japanese students aged 12–15 year old. No associations were found between living in wooden houses and asthma, respiratory symptoms (Daytime or nighttime breathlessness, wheeze, dry cough) or infections (Takaoka et al., 2014, 2017). Living in a wooden house was associated with dog allergy (OR: 2.17 (1.18; 4.00)) and mold allergy (OR: 1.98 (1.04; 3.76), but not with cat or pollen allergy (Takaoka et al., 2014). Furthermore, living in a wooden house was inversely correlated with living in a "multi-family house" and "window pane condensation", and correlated with "water leakage" (Takaoka et al., 2014) factors that are independently associated to adverse health effects.

Several studies on psychological and physiological effects in rooms with different wooden interior have been summarized in a review by Alapieti et al. (2020). The conclusion from the review indicates that wooden materials may provide a less stressful environment compared to other building materials. However, the number of participants in each study was low, participants were mostly students in their 20s and the time of exposure were 60-75 minutes. Thus, it is uncertain if the results reflect effects of long-term exposure in real-life.

Meklin et al. (2002) found higher risk of respiratory symptoms in children in both wooden and concrete/brick schools with moisture damage compared to children in non-moisture damaged schools. Stratified by construction type the associations were similar between wooden schools and concrete/brick schools with the exception of cough with phlegm (in spring) in wooden schools being higher than for concrete/brick schools (OR_{wooden} (95% CI): 2.25 (1.26; 4.02) vs. $OR_{concrete/brick}$ (95% CI): 1.27 (1.01; 1.60)). However, in this study it is difficult to disentangle the effects of mold vs. wood exposure.

Among primary school personnel in Sweden, participants in wooden schools reported fewer complaints due to stuffy nose compared to participants in brick schools, while nasal lavage biomarkers were not associated to construction materials (Wålinder, 2001).

Tear film stability (non-invasive tear film break up time (NIBUT) and self-reported break up time (SBUT)), subjective symptom frequency (often vs. sometimes or never), symptom indexes (general, mucosal and dermal) and perceived indoor work environment were assessed in a Norwegian study among 87 employees in three old brick buildings and 42 employees in an old wooden building (Bakke et al., 2011). Employees in the wooden building had better NIBUT and SBUT, fever subjective symptoms ("feeling heavy-headed", "Itching, burning or irritation of the eyes Irritated", "stuffy or runny nose" and "hoarse, dry throat"), lower scores on the general and mucosal index and less complaint on "stuffy air" than employees in the brick buildings. No differences were found for other subjective symptoms (fatigue, headache, nausea/dizziness, difficulties concentrating, cough, dry or flushed facial skin, scaling/itching scalp or ears, hand dry, itching, red skin), the dermal index or other environmental complaints (draught, temperature too high, varying temperature, temperature too low, dry air, unpleasant odor, static electricity, passive smoking, noise, inadequate illumination, dust and dirt). However, this study is prone to bias due to numerous possible confounders and thus, it is not possible to conclude if the associations are related to the structures of the buildings.

Building related symptoms

No associations between type of wall material (wood vs. stone) in the residence and prevalence of symptoms (eye, airway, dermal, or general symptoms) were found in a Swedish study of environmental, occupational, and personal factors among 466 participants from the general population (Norbäck & Edling, 1991). Weekly mucosal, general or skin symptoms during the past three months, were not associated with living in wooden house among 1084 students aged 12-15 year old in Japan (Takaoka et al., 2015). Mild building related symptoms ("Headache, heaviness in head, tinnitus", "Itching, burning, irritation, drying of the eyes", "Irritated, stuffy, or runny nose" or "Cough and sneeze") and characteristics of indoor environmental and individual factors were investigated in a nationwide questionnaire survey of 1500 adults in Japan. There was no association between living in a wooden house and any of the symptoms (Nakayama et al., 2019).

Satisfaction, perception, comfort

Cross-sectional studies

Occupants living in log-houses in Finland have been shown to report higher degree of "Satisfaction with indoor air quality" than people living in light-frame houses (Odds Ratio (OR) (95% Confidence Interval (CI)): 0.25 (0.10; 0.60)) and masonry/concrete houses (OR (95% CI): 0.16 (0.06; 0. 43) when adjusting for gender, age, marital status, agreeable temperature, ventilation, trickle vent and condensation in winter (Anttila et al., 2012). However, associations between construction type and occupants report of "Satisfaction with dwelling" were not significant when adjusting for gender, age, marital status, satisfaction with IAQ, agreeable temperature in winter and ventilation (OR (95% CI) for light-frame 0.73 (0.29; 1.85) and for masonry/concrete 0.52 (0.18; 1.49)). A study on 671 Japanese workers found the amount of wood used in bedrooms to be positively associated with comfort in bedrooms and sleep conditions. However, these effect indicators were not associated with wood structure of housing, wood floors, walls or ceilings (Morita et al., 2020).

Conclusion

The aim of this review was to summarize the existing literature on health effects associated with wooden constructions. The literature search resulted in sparse evidence on associations linking wooden construction to health. The search terms resulted however in an extensive body of literature on indoor pollutants, indoor air quality and the indoor environment specific to wooden buildings, and this has now been summarized in the report. It should be noted though, that the conclusions on indoor environmental conditions in wooden buildings do not reflect a systematic review of the existing literature on the indoor environment in wooden constructions.

The studies included in this report were most often performed on single family, single story houses. The investigated buildings were of various wooden constructions – wooden frame house, or log houses with varying amounts of exposed wood in the interior environment. No clear distinction was made between different types of wooden constructions, hence we were not able to identify differences within subtypes of wooden constructions.

In summary, the literature indicates conflicting results on the association between wooden construction and health. Due to the sparse literature, heterogeneity in the compiled studies and risk of bias within the studies, no clear conclusions can be drawn on this association. However, none of the included studies found an association between building related symptoms and living in wooden houses.

Wooden constructions and their building materials seem to be related to satisfaction, perception and comfort in a complex manner. The thermal environment in wooden constructions showed risk of overheating in warm climate and draught under cold conditions. However, the hygroscopic capacity of timber could reduce the variations in humidity, and thereby improve the comfort in wooden buildings. Impact noise was highly affected by the construction, floor materials and proximity to others, and was thus found to be a concern in lightweight wooden buildings. Odor from wooden materials did not affect comfort itself, but studies indicated that musty malodor is associated with degraded chlorophenols in wood preservatives.

Some studies found elevated VOC concentrations in indoor air in wooden buildings compared to average values or other types of constructions. Especially levels of terpenes, carbonyls (e.g. from OSB) and possibly formic acid, acetic acid and acetaldehyde may be elevated in wooden buildings. This should be, however, confirmed in future studies. The compiled literature indicates that other factors, e.g. age, type of material, season, ventilation, moisture content, type of heating and ozone concentration, may have a substantial impact on emissions in wooden buildings. Furthermore, VOC concentrations are strongly dependent on the position of the materials and on the emissions from other surface materials, such as OSB in construction and furniture. Formaldehyde levels have been associated with increased sensory irritation, risk of asthma, allergy and cancer. However, based on the included studies, no firm conclusion can be drawn on health effects related to formaldehyde exposure in wooden constructions.

This review demonstrates the need for further studies on health effects of wooden constructions. There is a need for epidemiological follow-up studies with objective measurements of health outcomes. Especially, there is a need for studies of the period from construction and through the first years of use. We found no studies on the effects of buildings and materials from multistore wooden constructions. Hence, there is an urgent need to study indoor air in modern wooden high-rise residential buildings. Furthermore, a better definition of “wooden construction” is warranted in order to be able to compare result across studies i.e. the classification into “Log house” “heavy Wood frame” and “Light Wood frame”.

Appendix A: Search strategy for scientific databases

Pubmed (no restrictions) 09.06.2020 Hits: 129			**Embase** (no restrictions) 30.05.2020 Hits 364 **Scopus** TITLE-ABS-KEY 30.05.2020 Hits 775		
Block 1 (OR) (combined with OR)	AND	Block 2 (combined with OR)	Block 1 (combined with OR)	AND	Block 2 (combined with OR)
"wood construction" "wood constructions" "wood building" "wood buildings" "wood house" "wood houses" "wood dwelling" "wooden construction" "wooden constructions" "wooden building” "wooden buildings" "wooden house" "wooden houses" "timber construction" "timber constructions" "timber buildings" "log houses" "log dwelling" "log homes"		"indoor air" "indoor climate" health allergy allergies "Allergic Rhinitis" Sensitivity Hypersensitivity Rhinitides nose respiratory "hay fever" hayfever asthma conjunctivitis "skin diseases" "skin irritation" dermatitis headache headaches tiredness fatigue sleep "indoor climate syndrome" "blood pressure" "heart rate" cardiovascular "Sick building syndrome" Comfort Satisfaction Productivity perception	"wood construction*" "wood building*" "wood house*" "wood dwelling*" "wood residence*" "wood home*" "wooden construction*" "wooden building*" "wooden house*" "wooden dwelling*" "wooden residence*” "wooden home*" "timber construction*" "timber building*" "timber house*" "timber dwelling*" "timber residence*" "timber home*" "log construction*" "log building*" "log house*" "log dwelling*" "log residence*" "log home*"		"indoor air" "indoor climate" health allerg* rhinitis sensitivity hypersensitivity nose respiratory "hay fever" Hayfever Asthma Conjunctivitis "skin disease*" "skin irritation" Dermatitis headache* tiredness fatigue sleep "indoor climate syndrome" "blood pressure" "heart rate" Cardiovascular “sick building syndrome" Comfort Satisfaction Productivity perception

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