Climate-based Performance of Wood/Heavy Timber Frame Construction in the Middle East – a Review

Final Report
Submitted to

Mme Aude Fournier
Expanding Market Opportunities Program
Natural Resources Canada | Canadian Forest Service

Denis Bourgeois, PhD
rd2 inc.

Québec, July 2013
Climate-based Performance of Wood/Heavy Timber Frame Construction in the Middle East – a Review
This report was prepared with the valuable contribution of Louis Saint-Pierre, consultant.
Overview

This work is a follow-up step to recent initiatives, supported by NRCan's Expanding Market Opportunities (EMO) program, in assessing the potential of expanding and diversifying Canadian wood exports, namely to the Middle East. Such initiatives include - but are not limited to – a recent market analysis report by the Walker Consulting Group\(^1\), and a recent mission to Qatar and the United Arab Emirates (UAE). Leading to this study, there was no published compendium of climate-based information for Canadian wood exporters to the Middle East, namely concerning wood-based building envelope assemblies and structures and in particular how such constructions would perform in the hot and humid regions of the Persian Gulf. Although for centuries, wood timbers have been used for structural purposes (ex. roofs) and essential architectural elements such as windows, doors, shutters and screens in the Arab World, wood-framed building envelopes are somewhat of a rare occurrence in Gulf countries. Expanding the use of wood in such ways, does open the door to legitimate questions of durability, robustness and safety (structural, fire), that need to be addressed. It is hoped that this work, which is at once a climate analysis and related literature review, serves as a basis for subsequent investigations.

As the literature suggests, habitable indoor environments of the Middle East are increasingly, and today overwhelmingly, mechanically air-conditioned. Thus any wood product destined for building interiors would be safely harboured from the climatic extremes of the Middle East, just as they would in any continuously air-conditioned environment in North America. Once in place, the material will reach and maintain some degree of hygrothermal equilibrium with the air-conditioned indoor environment. Whether that facility is built and operated in the Middle East or in North America, the fact that it is air-conditioned implies hygrothermal behaviour that is almost entirely unrelated to the fluctuating (and usually extreme) psychrometric\(^2\) states of the outdoor environment. As long as the air conditioning remains in operation, there shouldn’t be any hygrothermal issues with interior wood applications in Middle East facilities. Obvious examples include indoor furniture, kitchen cabinetry, hardwood flooring and subflooring, stairs, wooden doors, wooden window shutters, etc. Other, less obvious, examples include wood-studded interior walls and engineered wood floor/ceiling joists, which in some cases may structurally support the roof envelope assembly yet not be an integral part of the assembly itself (e.g. apparent ceiling joists supporting an above-deck insulated roof assembly). All of the above applications have previously been suggested as potential Canadian wood exports to the Middle East, yet their successful market penetration would be unrelated to any climate consideration, with the possible exception of potential termite damage – a more geographic than climatic concern. Other non-climatic, non-geographic concerns may apply, such as fire safety. Nonetheless, given the prevalence of air-conditioning in the Middle East, interior applications, although relevant as potential market exports, are not considered within the scope of this study.

Other potential uses of Canadian wood exports in the Middle East are exclusively exterior applications. Examples include exterior pergolas, shutters and other exterior shading devices, decking, guardrails, handrails, exterior furniture, etc. In addition to well-known issues of potential termite and UV damage, the analysis suggests that the extreme daily variability in temperature and ambient moisture content,

\(^1\) Middle East Market Analysis: Exploring the Opportunities for the Canadian Wood Industry in Saudi Arabia, UAE, Qatar, Kuwait, and Turkey (2012), Walker Consulting Group.

\(^2\) Psychrometrics is a branch of engineering concerned with the determination of physical and thermodynamic properties of gas-vapour mixes.
and thus of thermal expansion and/or wetting/drying of wood cells, may be a source of concern for coastal locations of the Middle East. Any subsequent risk assessment in this regard would require detailed knowledge of targeted materials, finishes and treatments, as well as their hygroscopic behaviour over time, preferably determined experimentally. Although there are publications on similar topics, it has not been possible to identify specific publications on recent exterior applications of wood products (e.g. exposed heavy timber) in the Middle East.

Finally, potential uses of Canadian wood exports in built environments of the Middle East include envelope assemblies, which generally consist of insulated walls and roofs, as well as exterior doors and windows. In addition to sharing some of the issues associated to exclusively outdoor or indoor applications (e.g. UV damage of exterior cladding, fire safety, potential termite damage), building envelope assemblies also incorporate risks associated to climate-related mass and heat transfer. Indeed, building envelopes are special applications as they buffer outdoor and indoor environments, mitigating between hot and cool, and dry and humid. These differences between often continuously changing psychrometric states of outdoor and indoor environments drive either heat and/or moisture flow through envelope assemblies. Accordingly, good building envelope designs integrate adequate water drainage management, continuous air barriers, continuous or overlapping insulation, etc., in order to minimize well-known risks of increased energy use, interstitial water condensation, rot, mold growth, etc. These are by far the most complex of applications to assess, and incorporate the greatest risk. Although topics relevant to all three wood-based applications (indoor, outdoor and envelope) are covered in this document (e.g. termites, daily cycling of ambient moisture content), the bulk of the work is focused on climate-related issues pertaining to building envelope assemblies.

Wood components in building envelope assemblies (e.g. walls, roofs) are precisely that: components, integrated within larger construction systems that typically includes insulation, exterior finishes or cladding, structural sheathing, air and water control layers, interior finishes or coverings, etc. The performance and long-term durability of a building envelope assembly depends, at various degrees, on how all of these components, once assembled together, behave as a whole. An insulated wood-framed wall may be well designed to suit the rigours of a very hot and humid environment (e.g. by integrating low water vapour permeable materials near the outdoor layers of the assembly, while maintaining highly permeable materials and finishes near the interior), yet may encounter issues down the road (e.g. rot, mold growth) if last-minute or poorly thought-out design decisions are made (e.g. applying a low-permeance vinyl wall covering). This indicates a potential added risk to exporting wood-based envelope assembly components, rather than entire assemblies: there’s a difference between marketing and exporting validated wood-based assemblies adapted to the Middle East, and marketing and exporting SPF framing components to a professional and industrial milieu unfamiliar with wood-based construction. Validation of suggested adaptations to wood-based (e.g. framed, CLT) envelope assemblies for the Middle East implies experimental and/or numerical testing (e.g. dynamic hygrothermal analysis) of proposed assemblies, ideally peer-reviewed by industry experts.

Certain building envelope designs or concepts are better suited to a given climate than others, or are alternatively robust enough to suit a wide range of climates. Remarkable work has been carried out over the years to help designers identify suitable envelope concepts for various climates. For instance, the Building Science Corporation offers in depth analysis and detailing of what their experts recommend as suitable envelope approaches for different climates, namely in the US, e.g. structural insulated panels

---

(SIPs) for Orlando’s hot and humid climate. This is not suggesting that other envelope concepts are not valid for the same climate; rather that attention should be paid to the specifics of each climate in relation to building envelope design, as presented in their documents. These initiatives rely on published climate classification methods. However, as discussed in greater detail in this report, existing climate classification methods do not paint an adequate picture of the general environmental conditions of the Middle East that may stress on typical North American wood-based building envelope systems. Indeed, in an attempt to better understand the climate of the Middle East with respect to building envelope design, analysis of published climate extremes and published annual climate time-series data was found necessary. Results clearly indicate that coastal locations of the Arabian Peninsula (< 25 km away from the coastline) are very hot and humid, similar to Orlando yet with greater daily variability and extremes, while inland locations are very hot and dry, similar to Phoenix yet again with greater variability and extremes. Building envelope assemblies well-suited for either Orlando or Phoenix are likely good candidates for the Middle East, requiring either minimal adaptations or some added degree of robustness appropriate for either Arabian Peninsula extremes.

Beyond climate analysis, little to no scientific material on the specific topic of wood-based building envelope assemblies and structures in the Middle East has been published to date, hinting at the need for Canadian wood exporters and partners to define and undertake R&D efforts to counter this knowledge gap. Nonetheless, the literature is rich with well-developed bodies of scientific knowledge that potentially give such efforts a head start. The literature provides a wealth of contextual information that would, in turn, be useful for wood exporters, such as what the competition is, their respective issues and what innovations are on the horizon. This in turn provides a basis of comparison when establishing the pros and cons of adopting wood-based systems. The literature also provides valuable information on building typologies expected to be built (e.g. multi-unit residential, schools, offices), their morphology (e.g. building heights, aspect ratios, fenestration), assumed operating conditions, standard heating, ventilating and air-conditioning (HVAC) practices, etc. Along with knowledge of regional climate, this information is critical in establishing an appropriate contextual framework from which the multi-criteria performance of wood-based systems can to be evaluated. The North American wood construction industry does know a fair deal of how such systems perform in similarly extreme climates of North America: there is a substantial body of scientific and empirical knowledge of what wood-based assemblies and systems work well in US hot-dry (e.g. Phoenix) and hot-humid (e.g. Orlando) climates, hinting that such designs may constitute suitable starting blocks for further fine-tuning of wood-based assemblies to suit the climate extremes of the Middle East.

Regardless of the suitability of future adaptations to known wood-based building envelope assemblies in response to the Middle East climate, other barriers remain, including unfamiliarity or uneasiness of local professionals and builders in specifying structural wood applications, lack of specific knowledge of building code requirements (i.e. under which conditions structural wood applications are considered code-compliant), etc. More than one source of information is generally required to adequately address each of the aforementioned barriers (more often in a complementary way): e.g. field surveys and interviews; networking with local professionals, builders and code officials; code and standards analysis; product literature. Often, current code requirements and current practices may fuel scientific research on whether current approaches achieve the desired objectives, or whether undesired side-effects are generated, potentially constituting the basis of subsequent code revisions. Sustained efforts towards gradually removing such barriers, targeting Middle East businesses and building owners, professionals and builders, as well as policy and code authorities, are required to support the increased integration of wood applications in the built environment of the Middle East.
Approach

The next few pages remind readers of the historical use of wood in Arab culture, either for essential architectural elements such as windows, doors and roof structures, or as a semi-precious building material. Some of the most geometrically intricate - and astonishing - wood works are found in the Arab World.

If one thinks of expanding the use of wood in this part of the world, e.g. a wider range of building envelope assemblies, then knowledge of regional climate is essential. Climate classification approaches are discussed, and an analysis of published climate data is presented, by contrasting North American and Middle East design conditions and typical weather data. A detailed analysis of the main driving forces behind water vapour migration through porous materials in building envelope assemblies is presented and discussed.

Beyond regional climate, an understanding of the architectural and cultural context of a given location is also essential if expanding the use of wood is intended. Questions concerning building typologies (i.e. what types of buildings are being built, what are their morphological characteristics?), current construction practices (i.e. competing industries, potential for hybrid approaches), anticipated innovations (i.e. how are competing industries adapting to new market demands), expectations of thermal comfort and related HVAC concepts and controls, as well as issues related to airtightness and workmanship are addressed through a detailed literature review. Risks of insect damage are also discussed, in light of published findings. Finally, a discussion on regulatory requirements is presented.
Recommendations

The following are recommendations, from general considerations to specific items, stemming from the overview and subsequent analysis.

- Canadian wood exporters should identify which potential barriers or limitations should be tackled in sequence, as some are more overarching than others. For instance, if there are code requirements in place with regards to termite control (e.g. treatment), then such requirements need to be addressed in priority with respect to those of a voluntary nature (e.g. industry best practices). Similarly, if a region’s building code limits the number of stories of wood-structured buildings to 3 in light of fire safety considerations, then it seems pointless to invest time and resources in adapting wood-based structures and envelope assemblies designed for 4- or 6-story buildings. Sequentially prioritizing this way provides a better (or more realistic) definition of the industry’s sandbox for a given market. Practical recommendations include getting up to speed with, and regularly maintaining knowledge of, regional building code requirements (e.g. what’s prohibited, what’s allowed and under what conditions, what’s coming up in the near future) on fire safety, termite control, energy efficiency, etc. This may require dedicated round tables, focus groups of Canadian industry experts regularly collaborating with local code experts and code authorities, etc., eventually providing easy-to-consult knowledge bases for exporters.

- Similar to the previous recommendation and in light of the industry’s perceived sandbox for a given market, Canadian wood exporters should prioritize products and applications which could more easily penetrate a new market with respect to those that require additional R&D efforts. Examples may include easily-packaged EnergyStar-rated (possibly aluminium-clad) wood windows and doors\(^4\), or interior applications such as engineered floor joists, kitchen cabinetry, etc., which are more easily integrated within otherwise masonry-based buildings, than wood-based wall assemblies. Prioritizing this way should allow a gradual, less risky penetration of Canadian exports over time, providing a solid basis for future expansion into wood exports that require sustained R&D efforts.

- Exporters interested in exclusively exterior applications (e.g. wood-based pergolas, shutters and other exterior shading devices) or even exterior wood-based cladding, should not only consider any regulatory barriers or requirements, but also the extreme temperature and ambient moisture levels of the Middle East regions of interest, in particular those of the coastal regions, (extremes, daily variations) that might affect thermal expansion and/or drying/moistening of wood cells. These extremes, although exceeding those observed for North America, may - in the end - be considered quite tolerable, yet arriving at such conclusions is beyond the scope of this work and likely requires the contribution of specialized industry experts.

- Exporters interested in wood-based building envelope assemblies or assembly components may rely on recommended best practices well-suited to North American hot and humid (e.g. Orlando) or hot and dry (e.g. Phoenix) climates as starting points. Subsequent adaptations to suit the more extreme climates of the Middle East should be based on appropriate experimental and/or numerical investigations (e.g. dynamic hygrothermal analysis). Such analyses are specific to envelope concepts and materials (e.g. CLT-based walls would likely require different

\[^4\] http://oee.nrcan.gc.ca/equipment/windows-doors/4753
adaptations than wood-framed assemblies with interstitial insulation). Careful consideration should be given to anticipated indoor conditions (e.g. air-conditioned housing, refrigerated storage), airtightness, and occasional wetting of external cladding due to irregular and rare (yet expected) thunderstorms, and potential solar-driven diffusion. An additional consideration relates to the likely operation of housing units under negative pressure regimes, particularly significant for hot and humid locations. A suggestion would be to collaborate with Canadian industry experts that have considerable knowledge with such concepts, experience with appropriate software, and/or possess calibrated models of typical or innovative wood-based envelope assemblies, as this may simply involve evaluating the same assembly under different climatic scenarios (i.e. a jump start).

- If assessing the energy performance of wood-based assemblies is intended (e.g. underlining potential advantages of a cost-effective, well-insulated wood-framed assembly in comparison to minimum code requirements for a given location of the Middle East), then attention should be paid to targeted building typology and morphology, as well as operational characteristics and anticipated HVAC systems, as the energy impact of any improvement would vary greatly in function to these variables.
Traditional Use of Wood in the Arab World

Wood (as with stone, adobe, brick, glass and various metals) has been for millennia, and remains, one of the key materials of the world’s vernacular architecture. However, because of its scarcity in much of the Arab world, wood as a resource acquired more of a semi-precious status; its use over the centuries being generally limited to applications where alternatives hardly – or simply do not - exist. Commonly known examples of wood use in the Arab World include “lightweight” roof structures, boat building, doors and windows, screens, furniture and ornamentation.

Beyond structural applications (where long – and therefore rare and expensive - timbers were often sought after), wood in the Arab World was generally treated as small pieces (as with ceramics), often achieving great artistic techniques of grille-work, screens, inlay and marquetry. Some of the most geometrically intricate - and astonishing - wood works of the world are found in Arab countries (Figure 1). One simply needs to Google Image “Islam arts wood” to marvel at some of the great wood works of the world.

Another well-known and interesting example of traditional Arab use of wood is the mashrabiya, lattice-framed openings – often projecting from the sides of buildings. Although some were built of carved stone, most are built from wood (framing and intricate lattice-work). Mashrabiya range from modest domestic examples to works of fine architecture as illustrated in Figure 2.

Figure 1 – A mashrabiya screen overlaid with ring design (taken from http://islamic-arts.org/2012/the-masterpiece-minbar)
Figure 2 - Wood-built Egyptian-style mashrabiya (taken from http://en.wikipedia.org/wiki/Mashrabiya)

Mashrabiya are not only spectacular cases of Arab artisanship, they are testimonials to urban vernacular practicality. The porosity offered by the lattice work (on three sides for projecting cases) increase localized airflow while maintaining privacy and shading. Occupants seeking increased airflow during warm conditions (compounded by high humidity levels in many regions of the Arab World) would often rest in these outdoor oriels while in the privacy of their own homes. Mashrabiya were often integrated to the second story or above.

Beyond a general appreciation of the great artisanship and artistic accomplishments of traditional Arab wood working, the preceding – and all too brief – comments on the use of wood in the Arab world
simply seek to establish that wood, although not as predominant as stone or brick in the Middle East, has been prevalent in Arab architecture for centuries. If there were any major objections to the use of wood in traditional Arab architecture, wood as a building material would have been routed out centuries ago.

This does not mean that the use of wood in the Arab World, and specifically in the Arabian Peninsula, isn’t without its challenges. As in many regions of the world, organic building materials are subjected to several sources of stress, including moisture, solar (UV, thermal expansion) and insects. These issues will be discussed in this document.

Although wood timbers have been used for structural purposes (ex. roofs) and essential architectural elements such as windows, doors, shutters and screens in the Arab World, wood-framed building envelopes (ex. wood-framed walls, familiar to North American buildings professionals) are somewhat of a rare occurrence in Gulf countries. Expanding the use of wood in such ways, especially with the use of “foreign” species such as Canadian spruce, pine and fir (SPF), does open the floor to legitimate questions on durability, robustness and safety (structural, fire), that need to be addressed. The longstanding use of wood in traditional Arab building culture nonetheless leads one to presume that there is no fundamental reason why its use could not be expanded (e.g. wider set of applications), as long as careful consideration is given to the aforementioned uncertainties.
Regional climate

Understanding a location’s climate allows one to better adapt construction systems to suit local environmental conditions. Contrary to meteorology, climatology focuses on understanding weather conditions in a certain geographical area averaged over a long period of time (e.g. 30 years, a century). Variables of interest include temperature (minimums, maximums, averages, daily ranges), air moisture content (relative humidity), solar contribution (sun paths, direct and diffuse irradiance distributions) and precipitation (annual and monthly rainfall). Depending on the task at hand (e.g. agriculture versus HVAC sizing, versus building envelope durability), certain variables become more important than others. Understanding the climate of key locations of interest in the Middle East, namely the United Arab Emirates (UAE), Kuwait and Saudi Arabia, is critical to successfully identifying necessary adaptations of standard Canadian (or rather North American) construction techniques to Middle Eastern conditions.

Climate Classification

The Köppen approach is one of the most widely used climate classification systems. First published by Russian-German climatologist Wladimir Köppen in 1884 (with subsequent modifications up until 1936), the system is based on the concept that native vegetation is the principal indicator of regional climate: annual and monthly precipitation and temperature profiles constitute the basis of the Köppen classification system. Figure 3 provides a world map of the Köppen system.

Figure 3 - World map of the Köppen-Geiger climate classification system. The Middle East, along with North Africa, Central and Western Australia and parts of South-West Africa and USA, are shown in red (Class BWh, i.e. “hot desert climate” with very little annual precipitation).

http://upload.wikimedia.org/wikipedia/commons/7/74/Koppen_World_Map.png
The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) developed a similar climate classification system (Briggs, Lucas & Taylor 2003a, 2003b), mainly with HVAC design purposes in mind. The ASHRAE climate classification system takes into consideration long-term regional temperature and precipitation (rainfall) variables, as follows:

Table 1 – ASHRAE climate classification, as found in ANSI/ASHRAE/IESNA Standard 90.1-2007 (Normative Appendix B)

<table>
<thead>
<tr>
<th>Zone #</th>
<th>Zone ID</th>
<th>Thermal Criteria (SI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A &amp; 1B</td>
<td>Very Hot-Humid (1A)</td>
<td>-Dry (1B)</td>
</tr>
<tr>
<td>2A &amp; 2B</td>
<td>Hot-Humid (2A)</td>
<td>-Dry (2B)</td>
</tr>
<tr>
<td>3A &amp; 3B</td>
<td>Warm-Humid (3A)</td>
<td>-Dry (3B)</td>
</tr>
<tr>
<td>3C</td>
<td>Warm-Marine (3C)</td>
<td></td>
</tr>
<tr>
<td>4A &amp; 4B</td>
<td>Mixed-Humid (4A)</td>
<td>-Dry (4B)</td>
</tr>
<tr>
<td>4C</td>
<td>Mixed-Marine (4C)</td>
<td></td>
</tr>
<tr>
<td>5A, 5B &amp; 5C</td>
<td>Cool-Humid (5A)</td>
<td>-Dry (5B)</td>
</tr>
<tr>
<td>6A &amp; 6B</td>
<td>Cold-Humid (6A)</td>
<td>-Dry (6B)</td>
</tr>
<tr>
<td>7</td>
<td>Very-Cold</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Subarctic</td>
<td></td>
</tr>
</tbody>
</table>

Where:

Marine (C) = Locations meeting all 4 of the following criteria:
1. Mean temperature of coldest month between -3 °C and 18 °C
2. Warmest month mean < 22 °C
3. At least 4 months with mean temperatures over 10 °C
4. Dry season in summer; the month with the heaviest precipitation in the cold season has at least 3 times as much precipitation as the month with the least precipitation in the rest of the year; the cold season is October through March in the Northern Hemisphere and April through September in the Southern Hemisphere.

Dry (B) = Locations meeting the following criteria:
Not marine, and:
\[ P < 2 \times (T + 7.0), \text{ where} \]
\[ P = \text{annual precipitation (cm)} \]
\[ T = \text{annual mean temperature (°C)} \]

Moist (A) = Locations that are not marine and not dry.

Köppen is a general classification system with agriculture first in mind, while the ASHRAE system, by design, is more suitable for HVAC (and to a lesser degree building envelope) design applications. Both are based on the assumption that regional precipitation correlates well with seasonal/annual air moisture content. This is true for North American locations (and many other locations worldwide). For instance, the American Southeast (e.g. Florida, Louisiana) and Hawaii - hot and humid - receive significant rainfall over the year, while the American Southwest (e.g. Arizona, New Mexico, Nevada) – hot and dry – receive very little. Yet both climate classification are misleading when applied to very hot and arid (i.e. little to no rainfall) climates along major bodies of water (e.g. arid regions in close proximity to the Mediterranean Sea, the Red Sea, the Arabian Sea, the Gulf of Aden, the Gulf of Oman and the Persian Gulf). There are other climate indices that have been developed over the years.
specifically with building envelope designs in mind (Cornick & Dalgliesh 2003, Lstiburek 2001, Scheffer 1971), but as they are all precipitation-dependent, they also are inadequate to characterize the hot-humid climates of the arid coastal regions of the Arabian Peninsula.

As Attia (2012) discusses in greater detail, arid locations of the Middle East and Africa a few dozen kilometers away from major bodies of water are best characterized – as expected - as very hot, with little ambient moisture content, thus validating the Köppen and ASHRAE classification systems. However, arid locations near the coastlines are more suitably characterized as very hot and very humid, despite having little to no precipitation. The ambient and solar energy absorbed by these large bodies of water (e.g. Persian Gulf), especially during the summer months, is so great that the massive evaporation from sea water saturates ambient air along coastlines.

Despite high temperatures and high humidity levels, coastal regions of the Arabian Peninsula are nonetheless characterized as “BWh” (i.e. desert) under the Köppen climate classification system, and as “1B – Very Hot-Dry” under the ASHRAE system - just as with dry locations further inland. In the case of very hot and arid coastal locations, it is clear that ambient moisture content does not necessarily correlate – in many cases, at all - with regional precipitation patterns. The transition from “very hot-humid” to “very hot-dry” near coastal Middle East locations can even take place along very short distances (e.g. a few dozen kilometres), as noted in Figure 4.

Research on the design, behaviour and performance of buildings and neighborhoods (e.g. materials, envelope systems, HVAC systems, energy management strategies, morphology) specifically in relation to the hot and humid conditions - and/or in relation to the contrast between coastal (humid) versus inland (dry) regions - of the Arabian Peninsula has been carried out by – but is not limited to - Budaiwi & Abdou
(2013); Sait (2013); Attia (2012); Al-Sallal & Al-Rais (2012, 2011); Budaiwi (2011); Fasiuddin, Budaiwi & Abdou (2010); Holm, Herkel & Pfafferott (2010); Ali & Alfalah (2010); Al-Mofeez (2010, 2007); Iqbal & Al-Homoud (2007); Al-Homoud, Abdou & Budaiwi (2005a, 2005b); Al-Homoud (2004); Alshaibani (2001); Saeed (2000). The authors either directly discuss this contrast in detail, or describe the climate of interest as matter of fact. The coastal regions of the Arabian Peninsula are indeed so humid, and combined with their low aridity, that they are considered ideal locations for humidity harvesting (Gandhidasan & Abualhamayel, 2010) and air-conditioning condensate water recovery. As reported in Guz (2005), around 9 million litres per year of air-conditioning condensate water is recovered at the Bahrain Airport Services for various uses (e.g. flushing, washing and landscape irrigation).

In summary, established climate classification systems do not paint an adequate picture of the general environmental conditions of the Middle East that may stress on North American wood-based building envelope systems. Indeed, to better understand the climate of the Middle East with respect to building envelope design, analysis of published climate extremes (for HVAC design purposes) and published annual climate time-series data is essential, and has been undertaken in this study (discussed later in this document). Given the abstract nature of the concepts and the technical proficiency required to understand their metrics, it is preferable to contrast the climate of the Middle East with North American climates, as follows, specifically with building envelope in mind.

Contrasting North American & Middle East Design Conditions

The literature does reveal some useful information on the very hot-humid and very hot-dry climates of the Middle East. Yet what does this climatic contrast initially mean for Canadian wood-based construction exports? Apart from a handful of “robust” building envelope assemblies, i.e. offering good performances in either hot/cold dry/humid condition (e.g. concrete sandwich panels, SIPs), conventional wood-based assemblies (at least those commonly built in North America) typically require some adaptation to suit either hot-dry or hot-humid conditions. Examples of simple adaptations include having a low permeance material/sheathing (e.g. vapour barrier) on the outside of assemblies in hot-humid conditions, while on the inside under hot-dry conditions. This entails that a Canadian manufacturer/builder interested in exporting wood-framed assemblies to the US, e.g. Phoenix (hot-dry) as well as Orlando (hot-humid), hopefully understands they are exporting/building two distinct products (albeit similarly-framed). Alternatively, if a Canadian manufacturer/builder instead prefers exporting/building a single, unique assembly to suit either US climatic extremes, e.g. suitable for both Phoenix and Orlando, then such an assembly would typically require adaptations towards some degree of “robustness” (usually at greater cost). An example would be to integrate rigid, low-permeance outboard insulation of sufficient thickness to prevent sheathing condensation in air-conditioned spaces under very hot-dry conditions (i.e. moisture migrating from indoors towards outdoors), while inhibiting ambient (outdoor) moisture migration inwards under very hot-humid conditions. In both wood-framed cases, airtightness is crucial to prevent localized “cold-spot” condensation.

The consideration of the above, it would likely be unadvisable in many cases for Canadian manufacturers to export a unique wall assembly to the Middle East without prior knowledge of the target location (coastal or inland), or alternatively adapting the assembly to achieve a high degree of robustness (and therefore suitable for the expected climatic extremes). The former isn’t without risk as
only a few dozen kilometres may separate coastal from inland locations, while the latter would generally imply increased production costs.

It would have been desirable to summarize here recently-published material, ideally scientific in nature (peer-reviewed), on tested or modelled adaptations of wood-based building envelope assemblies to suit either the very hot-dry or the very hot-humid conditions of the Arabian Peninsula, or both. It has not been possible to identify such work. This is unfortunate, but understandable given the rare use of wood as a construction material in large parts of the Middle East. It’s as if the hypothesis of wood-based building envelope assemblies wasn’t on the horizon, at least for active building researchers based in the Middle East. For instance, the bulk of the scientific literature dealing with building envelopes suited to the Arabian Peninsula (dry or humid), either as the main subject matter or discussed as a topic of secondary importance, can be categorized as either pertaining to masonry- or concrete-based systems (e.g. materials, block designs, insulation choice and thickness), or in a few exceptions aluminium-glass curtain walls increasingly popular for high profile, high-rise office towers (designs, issues, fenestration-to-wall ratios).

If little to no scientific material on this specific subject has been published to date, then an obvious recommendation at this point for Canadian wood exporters and associations - if the decision to move forward would indeed be made - is to start defining and undertaking a scientific research agenda to counter this knowledge gap, strategically prioritizing issues to address, complemented with field-based research on code-based limitations, perceptions, risks, etc. However, this does not imply that such a research agenda must start from scratch. As discussed in the following paragraphs, there are well-developed bodies of scientific knowledge that potentially give such an agenda a head start.

Although the literature doesn’t inform interested parties on how wood-based constructions perform - or would perform - in and around the Arabian Peninsula, it does provide a wealth of contextual information that would, in turn, be useful for such research. For instance, the literature informs wood exporters on what the competition is, their respective issues and what innovations are on the horizon. This in turn provides a basis of comparison when establishing the pros and cons of switching to wood-based systems. Similarly, the literature provides valuable information on building typologies expected to be built (e.g. multi-unit residential, schools, offices), their morphology (e.g. building heights, aspect ratios, fenestration), assumed operating conditions, standard HVAC practices, etc. Along with knowledge of regional climate, this information is critical in establishing an appropriate contextual framework against which the multi-criteria performance of wood-based systems is to be evaluated. This will be discussed in greater detail in subsequent sections.

Although the literature doesn’t reveal much on the performance of wood-based construction systems subjected to Middle East climate extremes, the North American wood construction industry (manufacturers, research support) does know a fair deal of how such systems perform in similarly extreme – yet not so extreme – climates of North America. There is a substantial body of scientific and empirical knowledge of what wood-based assemblies and systems work well in US hot-dry (e.g. Phoenix) and hot-humid (e.g. Orlando) climates. Many Canadian manufacturers export to such US locations and, as suggested earlier, have either integrated robustness as a design feature or have adapted their assemblies to suit either US climatic extreme. It is reasonable to assume that such adaptations or robust designs may constitute starting blocks for further fine-tuning of wood-based assemblies to suit the climate extremes of the Middle East. There is therefore value in comparing extreme North American against Middle East climate extremes, as follows.
The following sections compare the climates of representative locations of the Arabian Peninsula against known climatic extremes of North America, offering a first glance of the extent of potential adaptations. Seven locations are considered - three from North America: Ottawa (cold, a climate Canadians are familiar with); Orlando (US hot-humid); and Phoenix (US hot-dry) - four Middle East locations: Abu Dhabi (coastal, very hot-humid); Kuwait International Airport (desert, very hot-dry); nearby Kuwait Institute for Scientific Research (KISR) (coastal, very hot-humid); and Riyadh (desert, very hot-dry). Table 2 summarizes the geographical details of these seven locations.

Table 2 - Site Location Parameters

<table>
<thead>
<tr>
<th>Site</th>
<th>Latitude (°)</th>
<th>Longitude (°)</th>
<th>Time Zone</th>
<th>Elevation (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ottawa</td>
<td>45.32</td>
<td>-75.67</td>
<td>-5</td>
<td>114</td>
</tr>
<tr>
<td>Orlando</td>
<td>28.43</td>
<td>-81.33</td>
<td>-5</td>
<td>29</td>
</tr>
<tr>
<td>Phoenix</td>
<td>33.43</td>
<td>-112.02</td>
<td>-7</td>
<td>339</td>
</tr>
<tr>
<td>Abu Dhabi</td>
<td>24.43</td>
<td>+54.65</td>
<td>+4</td>
<td>27</td>
</tr>
<tr>
<td>Kuwait Int’l</td>
<td>29.22</td>
<td>+47.98</td>
<td>+3</td>
<td>55</td>
</tr>
<tr>
<td>Kuwait KISR</td>
<td>29.03</td>
<td>+47.98</td>
<td>+3</td>
<td>6</td>
</tr>
<tr>
<td>Riyadh</td>
<td>24.70</td>
<td>+46.80</td>
<td>+3</td>
<td>612</td>
</tr>
</tbody>
</table>

Table 3 presents the Köppen and ASHRAE climate classifications for all 7 targeted locations, as well their published heating (HDD) and cooling (CDD) degree-days (18.3 °C based) for comparison purposes. As discussed previously, all four Middle East locations are similarly categorized (BWh, 1B, Very Hot Dry), despite their contrasting climates. Comparison of HDD and CDD numbers are more revealing, at least with regards to annual trends in dry-bulb temperature (i.e. excluding the effects of ambient moisture). As expected, there is simply no comparison between Ottawa and all other targeted locations when it comes to both heating and cooling needs: Ottawa has roughly 4500 HDD while all other targeted locations have roughly 500 HDD or less, and Ottawa has only 236 CDD while all other locations have roughly 1800 CDD or more. With the exception of Abu Dhabi, which appears to essentially have no heating requirement (30 HDD), all other “hot” locations (US and Middle East) have HDD values ranging from 300 to 500. As such, it could be tentatively suggested that Middle East winter conditions are very similar to those of “hot” locations of the US. While Phoenix (one of the warmest climates in North America) has roughly 2500 CDD, all four Middle East locations have CDD values well above 3000, i.e. some of the warmest inhabited urban locations in the world.

Table 3 - Site Location Climate Data

<table>
<thead>
<tr>
<th>Köppen</th>
<th>ASHRAE 90.1/90.2 2007</th>
<th>ASHRAE 90.1/90.2 2007</th>
<th>HDD / CDD 18.3°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ottawa</td>
<td>Dfb</td>
<td>6A</td>
<td>Cold Humid</td>
</tr>
<tr>
<td>Orlando</td>
<td>Cfa</td>
<td>2A</td>
<td>Hot Humid</td>
</tr>
<tr>
<td>Phoenix</td>
<td>BWh</td>
<td>2B</td>
<td>Hot Dry</td>
</tr>
<tr>
<td>Abu Dhabi</td>
<td>BWh</td>
<td>1B</td>
<td>Very Hot Dry</td>
</tr>
<tr>
<td>Kuwait Int’l</td>
<td>BWh</td>
<td>1B</td>
<td>Very Hot Dry</td>
</tr>
<tr>
<td>Kuwait KISR</td>
<td>BWh</td>
<td>1B</td>
<td>Very Hot Dry</td>
</tr>
<tr>
<td>Riyadh</td>
<td>BWh</td>
<td>1B</td>
<td>Very Hot Dry</td>
</tr>
</tbody>
</table>
Heating and - more importantly - cooling degree-days are strictly based on recorded dry-bulb temperatures over time, and as such CDD comparisons do not reveal any information on ambient moisture content. For instance, one cannot establish if a location would be considered as hot-humid or hot-dry based on published HDD or CDD values. Yet this information is critical for building envelope design and analysis. One complementary source of useful data is published psychrometric design-day conditions, i.e. climate extremes that take into consideration air enthalpy conditions (sensible and latent heat), which serve as a basis for designing and sizing either building heating or cooling systems and equipment, as found in ASHRAE Fundamentals or publically-available climate data. 

Published climatic design values represent different extreme psychrometric conditions that are likely to occur for a given location. For instance, the ASHRAE Fundamentals Handbook (2013) provides, for hundreds of locations worldwide, three main psychrometric design conditions:

- Design conditions based on dry-bulb temperature, representing peak occurrences of the sensible component (i.e. excluding moisture) of ambient outdoor conditions. As complementary information, ASHRAE provides the mean wet-bulb temperature that coincides with the dry-bulb temperature-based design conditions.
- Design conditions based on wet-bulb temperature, which are related to the enthalpy of the outdoor air; enthalpy representing the sum of the sensible (dry air) and latent (moisture) energies of an air-vapour mix. As complementary information, ASHRAE provides the mean dry-bulb temperature that coincides with the wet-bulb temperature-based design conditions.
- Design conditions based on dew point, relating to the peaks of the humidity ratio; i.e. the mass ratio of water vapour to dry air for a given air-vapour mix. As complementary information, ASHRAE provides the mean dry-bulb temperature that coincides with the wet-bulb temperature-based design conditions.

There are additional design condition metrics, e.g. the mean daily dry-bulb temperature range, which is sometimes used in cooling load calculations.

The aforementioned conditions are often provided for different frequencies of occurrence (e.g. 98%, 99% or 99.6% of a given recorded period). The designer (or other) user must decide which set(s) of conditions and probability of occurrence apply to the (design) situation under consideration. For instance, as taken from the ASHRAE Fundamentals Handbook:

- The 0.4, 1.0, and 2.0% dry-bulb temperatures and mean coincident wet-bulb temperatures often represent conditions on hot, mostly sunny days. These are often used in sizing cooling equipment such as chillers or air-conditioning units.
- Design conditions based on wet-bulb temperature represent extremes of the total sensible plus latent heat of outdoor air. This information is useful for design of cooling towers, evaporative coolers, and outdoor-air ventilation systems.
- Design conditions based on dew-point temperatures are directly related to extremes of humidity ratio, which represent peak moisture loads from the weather. Extreme dew-point conditions may occur on days with moderate dry-bulb temperatures, resulting in high relative humidity. These values are especially useful for humidity control applications, such as desiccant cooling and dehumidification, cooling-based dehumidification, and outdoor-air ventilation

---

6 http://apps1.eere.energy.gov/buildings/energyplus/cfm/weather_data2.cfm?region=2_asia_wmo_region_2
systems. The values are also used as a check point when analyzing the behavior of cooling systems at part-load conditions, particularly when such systems are used for humidity control as a secondary function.

Although not specifically generated for building envelope applications in mind, these design conditions do provide useful information in characterizing – and comparing – different climates of the world. Table 4 provides dry-bulb temperature-based design conditions for the seven targeted locations. DB refers to design day (heating and cooling) dry-bulb temperature (0.4%), while MC WB refers to mean coincident thermodynamic wet-bulb temperature (with respect to the aforementioned cooling design day dry-bulb temperatures). Finally, the daily DB range refers to the summer design day dry-bulb temperature range. MC WB and the daily DB range are missing for KISR.

<table>
<thead>
<tr>
<th>Site Location</th>
<th>H DB 99.6% (°C)</th>
<th>C DB 99.6% (°C)</th>
<th>MC WB 99.6% (°C)</th>
<th>Daily DB Range (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ottawa</td>
<td>-24.5</td>
<td>30.6</td>
<td>21.6</td>
<td>10.1</td>
</tr>
<tr>
<td>Orlando</td>
<td>3.2</td>
<td>34.3</td>
<td>24.7</td>
<td>9.4</td>
</tr>
<tr>
<td>Phoenix</td>
<td>3.7</td>
<td>43.4</td>
<td>21.1</td>
<td>12.0</td>
</tr>
<tr>
<td>Abu Dhabi</td>
<td>11.5</td>
<td>44.9</td>
<td>23.2</td>
<td>12.5</td>
</tr>
<tr>
<td>Kuwait Int’l</td>
<td>4.1</td>
<td>47.9</td>
<td>20.9</td>
<td>15.6</td>
</tr>
<tr>
<td>Kuwait KISR</td>
<td>4.9</td>
<td>49.1</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Riyadh</td>
<td>5.9</td>
<td>44.2</td>
<td>18.7</td>
<td>13.5</td>
</tr>
</tbody>
</table>

Canadians are familiar with winter design day conditions around -25 °C DB, but how cold are the Middle Eastern locations in comparison? With a winter design temperature of 11.5 °C, it can be safely stated that heating equipment in any recent building in Abu Dhabi would very rarely – if ever – be in operation. The other three Middle East locations have winter design temperatures between 4 and 6 °C, only slightly higher than those of Orlando or Phoenix. One could therefore expect some form of auxiliary heating in operation during the coldest of winter nights of the latter three Middle Eastern locations, just as in Orlando and Phoenix – more so in single family dwellings.

How extreme are cooling design day conditions of the Middle East in comparison to North America? Not surprisingly, Ottawa has the lowest cooling design day conditions of the targeted locations, with the nearest of the warm climates being Orlando (hot and humid). Indeed, Canadians are familiar with hot and humid summer conditions for locations east of the Great Lakes (e.g. Toronto, Ottawa, Montreal). Relying strictly on published dry-bulb temperature-based cooling design day conditions (and without consideration of differences in altitude), Orlando has roughly 20% more ambient moisture content (e.g. grams of water vapour per kilograms of dry air) and approximately 20% greater enthalpy (sensible and latent energies of outdoor air) than Ottawa.

Comparison of cooling dry-bulb temperature-based design conditions may indeed provide useful information when it comes to assessing hot-dry versus hot-humid conditions. For instance, when comparing the combined effect of cooling design day dry-bulb and mean coincident thermodynamic wet-bulb temperatures, one can establish that Orlando has far greater design-day ambient moisture content than Phoenix (nearly three times as much), despite the latter having a design dry-bulb temperature of over 9 °C than that of Orlando (and thus having a far greater capacity to absorb water
vapour). In this case, the comparison validates that Orlando can be characterized as hot-humid, and Phoenix as hot-dry.

The ability to characterize climates as either hot-humid or hot-dry based strictly on their dry-bulb temperature-based design conditions cannot be generalized, however. Orlando has approximately twice the design humidity ratio (vapour to dry-air mass) than Abu Dhabi, which is only slightly higher than that of Phoenix. This may lead one to incorrectly assume that the climate of Abu Dhabi is closer to Phoenix (hot-dry) than to Orlando (hot-humid), which is far from being the case. Indeed, in many (extreme) cases, the dry-bulb temperatures may frequently peak well into the 40 °C for coastal regions of the Middle East, without its coincident ambient moisture content peaking with the same intensity. The methodology generating dry-bulb temperature design conditions doesn’t take into consideration ambient moisture in its selection process – it simply reports the mean coincident moisture content.

To get a better sense of a climate’s peak ambient moisture content, either evaporation (wet-bulb temperature-based) or dehumidification (dew-point temperature-based) design conditions are preferable. Table 5, taken from ASHRAE Fundamentals Handbook (2013), provides two distinct design conditions: “E WB” refers to the evaporation wet-bulb temperature-based design condition, while “DP” refers to dehumidification dew-point temperature-based design condition. In both cases, “MC DB” refers to their mean coincident dry-bulb temperatures, which are not taken into consideration in the selection process. The “HR” column indicates the humidity ratio, in reference to the dehumidification dew-point temperature. Unfortunately, there is no such published information for the Kuwait KISR station (although such information can be derived from archived KISR data).

Ottawa and Orlando (both hot-humid summers, but not to the same extent) exhibit a similar design-day characteristic: peak ambient moisture tends to occur at dry-bulb temperatures that are close to cooling design conditions (i.e. only a few degrees off), while the other locations have around a 10 °C difference between evaporation and cooling dry-bulb temperatures. This provides some justification in relying on more than one psychrometric design condition to adequately characterize climate extremes with regards to building envelope design and analysis.

<table>
<thead>
<tr>
<th>Site Location</th>
<th>E WB 99.6% (°C)</th>
<th>MC DB 99.6% (°C)</th>
<th>DP 99.6% (°C)</th>
<th>HR (kg H2O/kg air)</th>
<th>MC DB 99.6% (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ottawa</td>
<td>23.1</td>
<td>28.2</td>
<td>21.5</td>
<td>0.0164</td>
<td>25.7</td>
</tr>
<tr>
<td>Orlando</td>
<td>26.4</td>
<td>30.9</td>
<td>25.3</td>
<td>0.0206</td>
<td>27.7</td>
</tr>
<tr>
<td>Phoenix</td>
<td>24.5</td>
<td>35.8</td>
<td>21.8</td>
<td>0.0172</td>
<td>28.1</td>
</tr>
<tr>
<td>Abu Dhabi</td>
<td>30.6</td>
<td>35.3</td>
<td>29.4</td>
<td>0.0264</td>
<td>33.5</td>
</tr>
<tr>
<td>Kuwait Int’l</td>
<td>28.2</td>
<td>35.2</td>
<td>26.4</td>
<td>0.0220</td>
<td>32.6</td>
</tr>
<tr>
<td>Kuwait KISR</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Riyadh</td>
<td>20.2</td>
<td>36.4</td>
<td>17.2</td>
<td>0.0133</td>
<td>22.3</td>
</tr>
</tbody>
</table>

Riyadh clearly has the driest of the moisture-based design conditions, having the lowest of the evaporation wet-bulb and dehumidification dew point temperatures, as well as the lowest humidity ratios. Without information on the coastal Kuwait KISR station, Abu Dhabi sticks out with the most hot and humid design conditions, having the greatest of the evaporation wet-bulb and dehumidification dew-point temperatures, as well as the greatest humidity ratio. This paints a clearer climatic picture than strictly relying on dry-bulb temperature-based design conditions.
Orlando appears as an intermediate between Abu Dhabi on one hand and Riyadh on the other, i.e. Orlando's design humidity ratio lies halfway between values of either Arabian Peninsula extreme. This underlines one of the shortcomings of strictly relying on moisture-based design conditions to characterize climates: Orlando is, just like Abu Dhabi, a hot and humid climate – not some intermediate between very hot-humid and very hot-dry. Similarly, Phoenix appears as an intermediate between Ottawa and Orlando. If one were to consider moisture-based design conditions as criteria to characterize hot-dry versus hot-humid climates, then Ottawa (inaccurately) appears dryer than Phoenix. As a last example, the Kuwait Int’l Airport station appears as an intermediate between Orlando and Abu Dhabi: as discussed later in this document, the airport is best characterized as very hot-dry (not hot-humid as Orlando or Abu Dhabi). This shortcoming is attributable to the fact that design conditions are indeed climatic extremes and as such do not provide a frequency distribution of psychrometric states. The Kuwait Int’l airport may indeed have regularly-occurring peak enthalpy conditions exceeding in amplitude those of Orlando, but this does not mean such conditions occur very long or more frequently than those characterizing Orlando’s climate.

In summary, relying on either climate classification systems, heating/cooling degree-days, or published heating/cooling, evaporation or dehumidification design conditions – either in isolation or in combination – indeed provides useful knowledge of a location’s climate for building envelope design purposes, yet inevitably paints an incomplete picture of the climatic stresses than can impinge on wood-based constructions, namely with regards to frequency and duration.

**Contrasting North American & Middle East Typical Weather Data**

Analysis of annual, hourly-based time series data, synthesized from long-term archived meteorological observations (e.g. Environment Canada records from meteorological stations), constitutes a final source of useful climatic information. These data sets are compulsory input to building energy simulation applications. Contrary to design conditions, they do not represent extreme climatic conditions, but rather typical conditions of a given location (i.e. close to the average values observed over a given period, e.g. the last 30 years). As such, they should not be used for sizing of HVAC systems and equipment. Such data sets are also required for hygrothermal building envelope analysis tools, but it is always possible to use different climate data sets to better reflect the intended aim of a given investigation. For instance, typical long-term moisture balance assessment of an assembly should be carried out using typical weather data, while the durability of an assembly exposed to more severe conditions may require a more demanding scenario.

As discussed in Crawley & Huang (1997), different organizations developed their own methodologies to generate typical weather years to suit a particular need. As examples, ASHRAE, the National Renewable Energy Laboratory (NREL), the WATSUN Simulation Laboratory, and the California Energy Commission (CEC) have all released typical weather data sets to use for simulating building energy performance: WYEC2, TMY2, CWEC, and CTZ2, respectively. ASHRAE designed the WYEC2 data set to represent typical weather patterns, while NREL updated the TMY2 data sets to represent the most recent period of record available for work that requires insolation data (e.g. solar applications). WATSUN Simulation Laboratory created the CWEC weather data sets for use by the National Research Council Canada in developing and complying with the 1997 Model National Energy Code for Buildings (MNECB1997). All groups intended their weather data sets to be usable with energy simulation programs. Most data sets
are based on a monthly composite weighting of solar radiation, dry bulb temperature, dew point temperature, and wind velocity as compared to the long term distribution of those values. Months closest to the long term distribution are typically selected, and thus each resulting data set contains months from different years. Regarding the targeted locations, the source/format of Ottawa weather is CWEC; Orlando is TMY3; Phoenix is TMY2 (not all US locations have TMY3 data sets); Abu Dhabi and Riyadh are IWEC; while the Kuwaiti data have been generated by KISR. All weather data sets are downloadable from the US Department of Energy’s Energy Efficiency and Renewable Energy (EERE) EnergyPlus web site7.

The most likely period of the year when climatic stresses on building systems (e.g. envelope assemblies, HVAC systems and equipment) in the Middle East are greatest are undoubtedly the summer months (June, July and August). Vapour gradients across assemblies, which drive either indoor or outdoor vapour diffusion, are a function of ambient moisture content on either side of assemblies. For very hot-dry climates like Riyadh, maximum outward vapour gradients would occur during the summer when temperatures are peaking (and thus capable of holding a lot of water vapour). For very hot-humid coastal regions like Abu Dhabi, maximum inward vapour gradients would occur in summer when outdoor air reaches its peak moisture content. For this reason, the following tables – generated from typical year data sets – are presented for both annual and summer, i.e. June, July & August (JJA), periods.

There are other well-known variables that can affect vapour gradients, including solar-driven vapour diffusion (e.g. following a summer thunderstorm), as investigated by Derome, Karagiozis & Carmeliet (2010), as well as others. If such events were to occur (rarely, yet regularly) outside of the summer periods for a given location, then attention should be given to such phenomena for the periods of interest. Indeed, precipitation in the Arabian Peninsula mainly occurs during winter months. At this point however, there is little evidence that solar-driven diffusion would constitute a major source of concern for the Middle East locations of interest. Riyadh, for instance, has an annual precipitation of only 100 mm (an order of magnitude less than Orlando or Ottawa), and it falls essentially in winter. The climatic and meteorological characteristics of the UAE are discussed in great detail in de Villiers (2010).

Although one shouldn’t dodge this potential issue of solar-driven vapour diffusion altogether, it remains preferable to address this in greater detail in future hygrothermal analysis of candidate building envelope assemblies. So for remainder of this analysis, focus will be maintained on ambient environmental stresses that can occur during summer months.

Figures 5 and 6 compare maximum, minimum and average dry-bulb temperatures for all six locations, taken from their typical weather data sets. Without exception, all data sets hold more extreme conditions (maximums and minimums) than their heating and cooling design conditions in Table 4 (e.g. differences of around 2 °C in cooling). This is to be expected as design condition methodologies exclude the most extreme conditions encountered that occur for a limited number of hours. In general though, extremes follow closely design conditions, and comparisons between locations still hold true, e.g. KISR has the highest recorded temperature, Ottawa has the lowest, and so on.

Although Figure 5 provides average dry-bulb temperatures, this is of little use as it integrates seasonal variations (e.g. winter and summer). The averages provided in Figure 6 (JJA) are more revealing. Although noticeably warmer, all targeted Middle East locations have maximum and summer average

---

7 http://apps1.eere.energy.gov/buildings/energyplus/weatherdata_sources.cfm#TMY
dry-bulb temperatures approximately equal to those of Phoenix. A preliminary conclusion would be that, for a given set of indoor conditions (e.g. air-conditioned), a wood-based building envelope assembly appropriately designed for Phoenix should work well in similarly-dry locations of the Middle East (e.g. Riyadh, Kuwait Int’l). Some potential adaptations may be necessary, but they should be minor in nature (e.g. fine-tuning of insulation thickness).

Figure 5 – Dry bulb temperatures of selected locations (annual min, max, and averages)

For very hot-humid locations (e.g. Abu Dhabi, KISR) on the other hand, preliminary comparisons are not so straightforward. Orlando (hot-humid) has a JJA average dry-bulb temperature roughly 10 °C lower than Abu Dhabi or KISR. As well, minimum JJA temperatures for these Middle East locations do not drop below 25 °C, while their maximum JJA temperatures are significantly greater than that of Orlando. This indicates a much stronger (yet potential) ambient water vapour capacity than Orlando, which may suggest that wood-based envelope assemblies appropriately designed for Orlando could require some adaptation to suit the rigours of the hot-humid conditions of coastal locations of the Arabian Peninsula.

Figures 7 and 8 compare annual and JJA daily dry-bulb temperature ranges (i.e. temperature differences along any continuous 24-hour period) for all locations of interest. This information may be of some use when considering thermal expansion of exterior cladding or finishing systems, likely compounded by impinging solar radiation. Abdelrahman & Ahmad (1991) discuss such temperature fluctuations as an issue for uninsulated masonry wall construction in the Saudi Arabia. Both the annual and JJA (minimum, maximum and average) ranges for Phoenix are very similar to those of Middle East locations. This suggests that, all things being equal (including peak solar exposure), exterior cladding or finishing systems that have been adequately designed for Phoenix should be very well suited with regards to daily cycles of thermal expansion, temperature gradients, etc. This states nothing however on the
hygrothermal stresses of shipping Canadian SPF and other organic-based construction materials from Canada and built/installed in the Middle East.

**Figure 6 – Dry bulb temperatures of selected locations (June/July/August (JJA) min, max, and averages)**

**Figure 7 - Daily dry bulb temperature ranges (annual min, max, and averages)**
Beyond dry-bulb temperature patterns, typical weather data sets provide the necessary input to calculate hourly variations of outdoor partial pressure of water vapour (Pw), and by the same token water vapour gradients across building envelope assemblies. Water vapour held in moist air diffuses through porous material from places with a higher partial pressure to places with a lower partial pressure. The driving force of water vapour diffusion in porous material is the gradient of partial pressure. There are other driving forces behind moisture migration through materials (e.g. capillary transport), yet the focus is kept on diffusion as it can be assessed to a large degree without a priori knowledge of assembly composition. The parameters of interest to calculate outdoor partial pressures of water vapour (and other related psychrometric quantities), and comprised in typical weather data sets, are typically atmospheric pressure, dry-bulb temperature and any of the three major indicators of ambient moisture (e.g. wet-bulb temperature, dew-point temperature or relative humidity).

The first chapter of the ASHRAE Fundamentals Handbook (“Psychrometrics”) provides the necessary equations, coefficients and parameters to generate, with the use of typical weather data, hourly variations of outdoor partial pressure of water vapour. Typical weather data sets provided by US DOE (EPW format) integrate calculated values of relative humidity for every hour. Hourly variations of outdoor partial pressure of water vapour were generated simply by applying hourly variations of relative humidity to generated hourly values of dry-bulb temperature-dependent water vapour saturation pressures (Equations 5 and 6 of the Psychrometrics Chapter of the ASHRAE Fundamentals Handbook). Indoor values of partial pressure of water vapour can be similarly generated assuming indoor dry-bulb temperature and relative humidity, as discussed in further detail. Figures 9 and 10 provide annual and...
JJA calculated minimum, maximum and average values of ambient (outdoor) water vapour partial pressure for all seven locations of interest.

Figure 9 – Ambient water vapour partial pressure (Pw) (annual min, max, and averages)

Figure 10 - Ambient water vapour partial pressure (Pw) (June/July/August (JJA) min, max, and averages)
Contrary to Figures 5 through 8, which provide only an indication of the potential of ambient water vapour content, Figures 9 and 10 provide a more definitive assessment of typical ambient water vapour content for all seven locations. As such, the latter (and in particular Figure 10) provide a much more useful basis of comparison between climates of interest. Taking a closer look at Figure 10, the JJA average ambient water vapour partial pressure constitutes a good basis to compare hot-humid versus hot-dry climates. Orlando, Abu Dhabi and KISR are clearly comparable when it comes to ambient moisture content, with average JJA values well above 2 kPa. In fact, despite peak temperatures and peak water vapour partial pressures inferior to those of Abu Dhabi and KISR, Orlando sticks out as the most humid of all seven locations with an average JJA water vapour partial pressure of 2.8 kPa. More than any other indicator calculated thus far, this value (or comparison between values) provides an extremely strong argument in favour of exporting, to the coastal regions of the Arabian Peninsula, building envelope assemblies well-adapted to Orlando – i.e. if a system works well in central and southern Florida, then it should work equally well along the Arabian coastline, based on these values. Compounding effects to Orlando’s humid climate are the fact that Orlando’s JJA water vapour partial pressures never drop below 1.8 kPa (the closest is KISR with 806 Pa), an impediment to outdoor drying of cladding and sheathing materials, the very high likelihood of regular cladding wetting from precipitation, and the likelihood of solar-driven diffusion for Orlando (versus its unlikelihood for arid locations of the Middle East). These observations further reduce the perceived risk of exporting Orlando-friendly wood-based building envelope assemblies to the coastal regions of the Arabian Peninsula.

At the other extreme, Riyadh and Kuwait Int’l have average JJA water vapour partial pressures well below that of Phoenix. If Phoenix – a known hot-dry climate – is indeed dominated by outwards water vapour diffusion across envelope assemblies, then it should be expected – based on these numbers – that these driving forces would more than double for desert locations like Riyadh (i.e. average 584 Pa for Riyadh, in comparison to 1.387 kPa for Phoenix). Thus, contrary to hot-humid climates, building envelope assemblies well-suited for Phoenix may indeed require some degree of adaptation to counter this difference in outwards diffusion forces. Yet, Riyadh and Kuwait Int’l having on average warmer ambient temperatures than Phoenix, drying out of any moisture migrating through an assembly would be slightly facilitated in Riyadh and Kuwait Int’l in comparison to Phoenix.

Figure 10 also underlines the climatic contrast of the Middle East discussed in the few first pages of this document: despite being classified as hot-humid and hot-dry, the climates of Orlando and Phoenix, respectively, are much more alike (as well as Ottawa), then the climates of Riyadh and Abu Dhabi. This further emphasizes the commentary that a higher degree of robustness is likely required if a building envelope assembly is to suit both the very hot-dry and very hot-humid climates of the Arabian Peninsula.

The previous analysis attempts to classify the targeted Middle East locations as either hot-dry or hot-humid by comparison, i.e. one presumes that Abu Dhabi and Riyadh are essentially hot-humid and hot-dry, respectively, based on similar seasonal patterns of ambient water vapour partial pressures to those of Orlando (hot-humid) and Phoenix (hot dry), respectively. Again, the purpose is to establish whether diffusion forces (i.e. water vapour partial pressure gradients) are driving moisture inwards or outwards of building envelope assemblies. There is a more straightforward calculation, based on ambient water vapour partial pressures, that clearly establishes if the dominant diffusion forces are driving moisture outwards or inwards, yet this requires assumptions on the indoor operating conditions (e.g. indoor temperature and moisture content) to calculate gradients in water vapour partial pressures. Two
scenarios are considered. The first assumes a constant operating temperature of 24°C and a relative humidity of 60%, which is typical for fully air-conditioned environments (expected in the Middle East for the majority of recently built environments, including housing). The second scenario assumes a warmer temperature of 30°C and 45% relative humidity. The latter scenario would be rated as being uncomfortable by most building occupants, yet is evocative of certain environments: examples include light to heavy industrial facilities, partially air-conditioned storage facilities, and partially air-conditioned housing (long-term and short-term). Based on these two scenarios, hourly differences between indoor and outdoor water vapour partial pressures can be generated. Figures 11 and 12 illustrate minimum, maximum and average differences in water vapour partial pressure (ΔPw), for the year and JJA, for the first indoor scenario. Figures 13 and 14 present similar information, yet for the second indoor scenario. Negative values of ΔPw indicate drier outdoor environments than indoors, thus outwards-driven moisture migration; positive values indicate wetter outdoor environments than indoors, and therefore inwards-driven moisture migration.

Figure 11 – Water vapour partial pressure difference (ΔPw), indoor DBT/RH 24°C/60% (annual min, max, and averages)

From Figure 11, one can establish that Ottawa, Phoenix, Kuwait Int’l and Riyadh are dominated by outwards-driven moisture migration over the course of a year; Orlando and Abu Dhabi are clearly more humid and thus dominated by inwards-driven moisture migration. Yet again, annual statistics provide a skewed assessment as they often cancel out important seasonal differences. Figure 12 provides a clear picture of JJA patterns for the first indoor scenario. As discussed previously, Orlando sticks out as the most stable of the climates (i.e. less difference in the extremes) and is clearly dominated by inwards-driven moisture migration. In fact, there are no JJA hours with outwards-driven moisture migration, based on Orlando typical weather data. Abu Dhabi and KISR are also dominated with inwards-driven moisture migration, yet with much stronger extremes: both locations can encounter occasional, yet extreme humid conditions (far superior to extremes of Orlando), and also extreme dry conditions that
are in the same range than those of Riyadh. So although Orlando remains the most humid of the climates with a JJA average $\Delta P_w$ of roughly 1 kPa, the observed extremes of the Abu Dhabi and KISR climates would justify taking a closer look, through future hygrothermal analysis of candidate envelope assemblies, of such extreme, yet rare, humid/dry cycles. Riyadh and Kuwait Int’l are clearly dryer than Phoenix with a JJA average $\Delta P_w$ of roughly -1 kPa (outwards-driven), although Kuwait Int’l also experiences wet/dry extremes that warrant some consideration.

Figure 12 - Water vapour partial pressure difference ($\Delta P_w$), indoor DBT/RH 24°C/60% (JJA min, max, and averages)

Both Figures 13 and 14 (annual and JJA values for the second indoor scenario) present similar statistics to those in Figures 11 and 12, yet with an offset of approximately 120 Pa (i.e. there is slightly more indoor moisture in the second scenario). This means that for humid locations such as Orlando, Abu Dhabi and KISR, inwards-driven moisture gradients have been reduced by 5% to 10%. Inversely, such gradients have increased by 10% to 20% for dry locations such as Phoenix, Riyadh and Kuwait Int’l. Varying hypothetical indoor conditions this way provides a potential range of extreme and average moisture conditions that govern driving forces conditioning moisture migration within building envelope assemblies. For instance, if inwards-driven moisture migration is a perceived source of risk, then establishing hypothetically-dryer indoor conditions would be suggested (e.g. 23 °C and 40% relative humidity, or even dryer environments such as refrigerated warehouses). This really depends on the targeted locations, building types and expected operations, etc.
Figures 13 and 14 compare annual and JJA minimum, maximum and average $\Delta P_w$ ranges along any continuous 24-hour period for all locations of interest, under the first indoor scenario (24 °C and 60%
relative humidity). High values suggest large(r), short-term (e.g. daily) variations in exterior cladding and sheathing material moisture content. Comparing values in both figures, it can be established that Orlando, Phoenix and Riyadh, considered the most stable or constant of the climates, experience their extreme daily variations outside of the JJA period, and are generally mild in comparison to those of the other locations. Although Kuwait Int’l has an average JJA ΔPw range similar to those of North American locations, it encounters extremes in JJA ΔPw range that are two to three times greater than those of North American locations. Not only do Abu Dhabi and KISR have even greater JJA ΔPw range extremes (> 3 kPa), they encounter average JJA ΔPw ranges that are also two to three times greater than those of any other location. So for Abu Dhabi and KISR, the very hot-humid coastal locations of the Arabian Peninsula, there are clearly strong daily cycles in ambient moisture content, which could affect daily wetting/drying cycles of cladding and sheathing materials in wood-based building envelope assemblies. It would thus be advisable for Canadian exporters of wood-based cladding and exterior sheathing materials to carry out a risk assessment of related issues (e.g. premature aging), first through industry consultation (e.g. round table discussions) and potentially through numerical and experimental investigations.

Figure 15 - Daily range of water vapour partial pressure difference (ΔPw) (annual min, max, averages), 24°C/60% RH
The bulk of the preceding analysis is focused on moisture transport across opaque building envelope assemblies (e.g. walls, roofs), which constitutes one of the most critical of climate-based concerns in the construction industry. There are additional contexts where ambient moisture, and other environmental variables (e.g. UV), may also be an issue. Examples include exterior-only applications of wood-based constructions (e.g. pergolas and other exterior shading devices, wood-based structures of outdoor sports facilities, exterior furniture). In such cases, it is possible that the extreme variability in temperature and ambient moisture content, and thus of wetting/drying of wood cells, in coastal locations of the Middle East may be a source of concern. Yet such risk assessments require detailed knowledge of targeted materials, finishes and treatments, as well as their hygroscopic behaviour over time, preferably determined experimentally. Although there are publications on similar topics (Lepage, 2012), it has not been possible to identify specific publications on recent exterior applications of wood products (e.g. exposed heavy timber) in the Middle East.

Fully-interior applications of wood-based constructions (e.g. CLT roof structure of an air-conditioned sports facility) are another matter. Once in place, the material will reach some degree of hygrothermal equilibrium with the air-conditioned indoor environment. Whether that facility is built and operated in the Middle East or in North America, the fact that it is air-conditioned implies hygrothermal behaviour that is almost entirely unrelated to the fluctuating (and usually extreme) psychrometric states of the outdoor environment. As long as the air conditioning remains in operation, there shouldn’t be any hygrothermal issues with interior wood applications in Middle East facilities.
Built environments

The preceding climate analysis, in particular the commentary on differential water vapour partial pressures across building envelope assemblies, illustrates the necessity of clearly defining the indoor climate that is being separated by the assembly from the outdoor climate. The preceding discussion deals with differences in enthalpy between indoor and outdoor environments, yet related considerations, such as energy use, require additional variables such as building morphology, operational characteristics, HVAC systems, etc., as well as typical assemblies against which wood-based constructions are to be compared. Which specific Middle East market segments are targeted by Canadian wood exports: single family dwellings, multi-unit residential buildings (MURBs), retail, small-scale educational buildings such as schools and mosques, or all of the above? Are they envelope-load (e.g. residential) or internal-load (e.g. offices) dominated? Are targeted residential or commercial vocations high-end or aimed at upper middle classes? One can usually associate to each of these segments particular requirements or expectations, e.g. in terms of behaviour, costs, building code requirements, basic layouts, number of stories, typical HVAC approaches, and so on. It is far beyond the scope of a literature review to isolate and answer each of these questions. Nonetheless, these questions do require answers if useful assessments (e.g. energy performance) are to be carried out in the future. The following aspects have been touched on by previous authors. It is hoped that this overview may be useful in narrowing down issues specific to targeted niche markets, at least in the short-term.

Building type

Al-Mofeez (2010, 2007, and 2006) compared predicted versus actual energy savings of retrofitted single-family dwellings in Dhahran, Saudi Arabia. Ahmad (2004) compared the energy performance of different wall and roof construction materials for a typical house also located in Dhahran. Papers provide detailed floor plans and elevations of investigated houses. Budaiwi & Abdou (2013) investigated the impact of thermal conductivity changes due to wetting of fibrous insulation on the energy consumption of residential buildings in the hot-humid regions of Saudi Arabia. Similarly, Al-Saadi & Budaiwi (2007) looked into the energy performance of envelope designs for a two-story, single-family dwelling for both Riyadh (dry) and Dhahran (humid) climates. Architectural characteristics were generated from polled housing designers. Said & Al-Hammad (1993) evaluated the impact of wall and roof insulation measures on the energy use of a typical two-story residential building in Saudi Arabia. Similar research was carried out by Alajnan, Smiai & Elani (1998). Holm, Herkel & Pfafferott (2010) explored innovative concepts for a set of net-zero houses in Dubai. Numan, Almaziad & Al-Khaja (1999) conducted an energy performance analysis for a typical residential building in the Gulf region, dealing with variations in geometry, orientation, glazing and solar obstructions. Abdelrahman, Said & Ahmad (1993) evaluated the energy performance of different masonry units integrated in four model single family dwellings. Al-Masri & Abu-Hijleh (2012) investigated the effect of integrating traditional courtyards to midrise MURBs in Dubai, and commented on the current practice of building 4- to 6-story MURBs. Radhi, Eltrapolsi & Sharples (2009) explored whether the new Bahraini building energy regulation would improve thermal comfort in residential units. Attia (2012) makes compelling arguments in favour of concentrating efforts on MURBs (Figure 17); the residential sector in Egypt consuming more than 47% of the total national generated electricity (essentially due to air-conditioning).
Iqbal & Al-Homoud (2007) carried out a parametric analysis of alternative energy conservation measures in an office building in Dammam, Saudi Arabia. Al-Homoud (2004b) evaluated the effectiveness of thermal insulation in Riyadh and Dhahran for single-story residential as well as office buildings. Al-Homoud (1997) had previously compared the energy optimization of office building design, of various sizes, for US and Saudi locations. Assem & Al-Mumin (2010) investigated the effect of glazing type and energy conservation measures on the peak power demand of air-conditioning in tall (> 14 stories) to super-tall (> 85 stories), highly-glazed office towers in Kuwait. Hasnain et al (1997) carried out a detailed energy audit and analysis on a 6-story office building in Riyadh. Radhi (2009a) compared the accuracy of building energy simulation results using different weather periods applied to low-rise and high-rise office buildings in Bahrain. Using the same office models, Radhi (2009b) investigated the potential of new Bahraini building envelope standards to achieve state objectives in energy conservation. Factoring in available rooftop area for PV and solar harvesting, Canada’s RWDI (Phillips, Beyers & Good 2009) estimated that a net zero office building in Abu Dhabi would have to be limited to two stories in height, based on energy simulation analysis of a hypothetical office building, if building-integrated renewable energy systems were to address the building’s requirements. The authors suggest the possibility of stretching this to three to five stories in height if internal gains are aggressively reduced through controls, daylighting, etc.

In summary, the literature provides useful typological and morphological variables as input for simulation-based investigations on residential (single-family dwellings, MURBs), office buildings (from low-rise to skyscrapers), educational buildings and mosques; investigations on other typologies would require new field data. Table 6 summarizes the main findings with regards to typology and morphology.

Table 6 – Summary of typological and morphological parameters of previously-investigated buildings

<table>
<thead>
<tr>
<th>Source</th>
<th>Type</th>
<th>Shape</th>
<th>Floor Area</th>
<th># stories</th>
<th>Ceiling Height</th>
<th>FWR %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abdelrahman et al (1993)</td>
<td>Dwelling</td>
<td>Rectangular</td>
<td>266 m²</td>
<td>2</td>
<td>3.3 m</td>
<td>13 %</td>
</tr>
<tr>
<td>Ahmad (2004)</td>
<td>Dwelling</td>
<td>Rectangular</td>
<td>263 m²</td>
<td>2</td>
<td>3.5 m</td>
<td>13 %</td>
</tr>
<tr>
<td>Al-Homoud (2004b)</td>
<td>MURB</td>
<td>Rectangular</td>
<td>600 m²</td>
<td>1</td>
<td>3.5 m</td>
<td>20 %</td>
</tr>
<tr>
<td>Al-Masri &amp; Abu-Hijleh (2012)</td>
<td>MURB</td>
<td>Rectangular</td>
<td>717 m²</td>
<td>6</td>
<td>3.5 m</td>
<td>20 %</td>
</tr>
<tr>
<td>Al-Mofeez (2007)</td>
<td>Dwelling</td>
<td>Rectangular</td>
<td>319 m²</td>
<td>1</td>
<td>3.2 m</td>
<td>16 %</td>
</tr>
<tr>
<td>Iqbal &amp; Al-Homoud (2007)</td>
<td>Office</td>
<td>Rectangular</td>
<td>417 m²</td>
<td>6</td>
<td>5.3 m</td>
<td>40 %</td>
</tr>
<tr>
<td>Radhi et al (2009)</td>
<td>Dwelling</td>
<td>Irregular</td>
<td>215 m²</td>
<td>1</td>
<td>3.5 m</td>
<td>20 %</td>
</tr>
<tr>
<td>Attia (2012)</td>
<td>MURB</td>
<td>Rectangular</td>
<td>600 m²</td>
<td>9</td>
<td>2.7 m</td>
<td>42 %</td>
</tr>
</tbody>
</table>

Current Construction Practices and Anticipated Innovations

The literature provides several references to standard construction practices (structural, envelope), from low-end (often non code-compliant) to well-insulated wall and roof systems, R&D efforts and innovations to improve current practices, trends in fenestration, etc. For Canadian wood exporters, this describes what the competition is, i.e. a solid basis for comparison.

The most commonly encountered construction technique for small-scale to mid-rise housing and commercial buildings in the Middle East is as follows: slab-on-grade, reinforced concrete structure and roof decking, plastered masonry infill (e.g. concrete masonry units or CMU). Windows are often single-pane (low-end), yet increasingly double-glazed, sealed units. Integrating insulating materials within walls and roofs is increasingly considered as common practice, and is code required in many areas. It however appears likely that - in many cases, non-compliant - uninsulated systems are still being built in the Middle East, despite evidence in support of good insulation practices and material availability (Al-Jabri et al 2005, Al-Homoud 2004b). Attia (2012), Al-Mofeez (2007) and Al-Homoud (2004b) defined uninsulated brick or CMU walls as reference construction for housing. Ahmad (2004) investigated reductions in housing air-conditioning consumption in Dhahran by insulating roofs and replacing uninsulated CMU with gypsum blocks or by adding wall insulation. The use of gypsum block provided a reduction of 13 %, while wall insulation generated savings of 42 %. Abdelrahman, Said & Ahmad (1993) had previously
compared the energy performance and cost effectiveness of ( uninsulated) clay bricks, sandlime bricks, and prefabricated concrete panels to CMU, while Abdelrahman & Ahmad (1991) had evaluated the cost-effectiveness of insulating various masonry wall systems (e.g. clay brick, CMU). Al-Sanea (2002) and Al-Sanea & Zedan (2007) looked into the thermal performance of insulating roof and wall elements with respect to uninsulated reference constructions. Maghrabi (2005) compared thermal insulation alternatives for walls and roofs in Makkah.

With the prevalence of CMU and other masonry units in wall assemblies on one hand, and increasing performance expectations in the Middle East on the other, it is expected that local industries seek CMU and other masonry unit performance enhancements through R&D. Al-Hammad & al (1994) had initially compared tested insulation material conductivities against published manufacturer values for over 14 Saudi manufacturers. Results indicated that published values do not necessarily represent proper values for Saudi climatic conditions. Al-Hadhrami & Ahmad (2009) tested the contribution of different insulation innovations on nine types of clay masonry blocks and two types of CMU used in Saudi Arabia, either by adding insulation within the masonry mix (polystyrene or perlite) or by insulating masonry cavities (or both), in addition to using insulating mortar. Significant increases in unit thermal resistance are observed, more so for CMU as clay bricks are initially less conductive. The authors suggested however that adding insulation to the masonry mix may render them more susceptible to moisture absorption in hot-humid climates. Al-Jabri et al (2005) investigated the performance improvements to lightweight CMU by changing cavity designs, as well as innovative CMU designs integrating sandwiched insulation. Al-Jabri et al (2009) evaluated the structural and insulating effects of using local waste material (e.g. recycled polystyrene beads from packaging, cement kiln dust) as insulating agents within lightweight CMU. Antar & Baig (2009) and Antar (2010) looked into reducing conjugate conduction-convection heat transfer in masonry cavities, as well as surface emissivity, as means of increasing masonry thermal resistance (20% to 30%). Budaiwi & Abdou (2005) investigated the temperature-conductivity relationship for locally-produced insulation materials. Energy savings from different wall insulation materials and thicknesses, among other variables, were evaluated by Al-Masri & Abu-Hijleh (2012).

Many of the preceding papers provide detailed tables on commonly-used local materials, as well as innovative materials and designs (e.g. attributes such conductivities, densities, resulting R-values), including Saleh (1990), Abdelrahman & Ahmad (1991), Al-Hammad & al (1994), Al-Sanea (2002), Budaiwi & Abdou (2005), Al-Jabri et al (2005, 2009), Antar (2010), and Al-Masri & Abu-Hijleh (2012).

**Thermal Comfort, Temperature Control & HVAC**

For hygrothermal analysis as well as energy performance assessments, reasonable assumptions on anticipated indoor thermal environments are required. The prior analysis on water vapour partial pressure differences required such assumptions. For residential, educational, commercial and office environments, most authors tend to assume year-round mechanical air-conditioning and typical cooling temperature setpoints between 24 °C and 25 °C, or around 76 F, which are aligned with Western expectations (Abdelrahman, Said & Ahmad 1993, Al-Sanea 2002, Ahmad 2004, Al-Homoud 2004b, Iqbal & Al-Homoud 2007, Al-Mofeez 2007 & 2010).

Temperature setbacks during unoccupied periods (e.g. nighttime, weekends) are increasingly common as a means of saving energy, with control strategies based on cooling setback temperatures of 26 °C to
27 °C (Al-Homoud 2004b, 2007). In addition to setbacks during unoccupied periods, Al-Sanea & Zedan (2008) calculated the energy savings from dynamically resetting heating and cooling setpoints on a monthly basis, rather than annual settings, as a function of thermal expectations and seasonal clothing habits. Savings were in the order of 27 % to 34 %, while peak demand savings in summer were between 14 % and 26 %. Al-ajmi & al (2006, 2008) measured clothing thermal insulation and area factors of typical Arabian Gulf clothing ensembles for males and females. Al-ajmi & Loveday (2010) subsequently surveyed occupant thermal preferences in Kuwaiti domestic buildings and found that neutral operative temperatures based on Actual Mean Vote (AMV) and Predicted Mean Vote (PMV) were 25.2 °C and 23.3 °C, respectively, in summer. Such differences could generate savings of around 10 % in cooling energy as well as reductions in peak demand in Kuwait. Al-Dabbous et al (2013) also found similar discrepancies. When evaluating either the hygrothermal response or the energy performance of wood-based envelope assemblies, such variations in operating temperatures should be taken into account.

Although mechanical air-conditioning is prevalent - even de facto code-required (see Table 7) in many cases- in the Arabian Peninsula, there is quite a large variation in chosen HVAC systems and operation (e.g. from window air-conditioners and split systems to central cooling plants). Ceiling fans are sometimes used in a complementary way to air-conditioning (Al-Mofeez & Numan 2004). All of the above energy use assessments required, in some form or another, various assumptions on heating, cooling and ventilation equipment (e.g. type, cooling coefficient of performance or COP) and operation.

### Table 7 - Acceptable range of indoor thermal conditions, part of Dubai’s Green Building Regulations & Specifications (Government of Dubai 2011)

<table>
<thead>
<tr>
<th></th>
<th>Lower Limit</th>
<th>Upper Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry bulb temperature</td>
<td>22.5 °C</td>
<td>25.5 °C</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>30% RH</td>
<td>60% RH</td>
</tr>
</tbody>
</table>


### Airtightness & Workmanship

Adequate control of air movement through and within insulated building envelope assemblies is just as important, if not more so, than managing moisture migration by diffusion. Despite the abundant literature (e.g. research, guide material) on the topic in Canada and in the US, as well as in Europe, designing, commissioning and maintaining airtight buildings remains a challenge.

Most of the reviewed papers that do mention natural infiltration deal with energy assessments: (assumed) infiltration rates are a necessary input to carry out energy simulation evaluations. Yet there isn’t a single mention of airtightness measurements carried out in the Arabian Peninsula in these papers. This is somewhat surprising given the estimated impacts of infiltration in comparison to other energy transfer mechanisms. Ahmad (2004) broke down energy consumption sources of a simulated house in
Dhahran. Energy use due to infiltration was estimated at 22%, while energy requirements to counter solar loads through glazing were evaluated at 17%. Solar treatment of windows is a common topic, but very little is mentioned about infiltration.

There is another aspect to natural infiltration one shouldn’t ignore when considering dwellings and MURBs in the Middle East: based on the literature, it would seem that while mechanical air-conditioning is widespread (e.g. split units), balanced ventilation systems are a rare occurrence. This means building designers, builders and owners are relying on natural infiltration to ensure indoor air quality (IAQ). There may be localized extraction ventilation in bathrooms and kitchens, yet likely without compensating air supplies, implying that many residential units are operating under negative pressures. That may be somewhat safe in very hot-dry locations, but in very hot-humid climates this means regularly drawing-in moist air through insulated envelopes, in which its successive layers, from outdoor to indoors, get increasingly colder until indoor conditions (e.g. 24 °C, 50% relative humidity) are reached. It is unclear at this point how serious an issue this may be in the hot-humid climate of the coastal regions of the Arabian Peninsula. But such an issue would certainly be more problematic if organic materials (e.g. wood framing, cellulose insulation, wood-based sheathing) are integrated within assemblies. In addition, the quality of the workmanship necessary to successfully build airtightness buildings should not be underestimated. Workmanship, as a potential issue, is briefly discussed in the literature (Al-Jabri & al 2005).

In summary, airtightness is an important issue to keep in mind, not only from an energy standpoint but also from a durability perspective, in particular for wood-based constructions in very hot-humid conditions. Providing well-designed, well-executed airtight buildings may on one hand be an admirable and cost-effective solution, it would require on the other providing balanced ventilation as a corollary. It is recommended that future investigations be carried out (numerical and/or experimental evaluations, consultation among industry experts, etc.) into the risks of integrating wood-based constructions in residential units running under negative pressure regimes in very hot and humid conditions, potentially compounded by poor airtightness.
Insects

Foraging insects, such as termites and ants, are found throughout the world except in the coldest of regions. In nature, termites forage through cellulose content (e.g. wood, leaves), converting it back into soil, improving its structure and fertility. Termites do not distinguish between cellulose found in nature and that in artifacts. Faragalla (1983) observed that huge piles of cellulose debris (e.g. cardboard boxes, paper) were attacked and decomposed back into soil through termite activity. Whereas earthworms enrich the soil in cooler and wetter latitudes, Evans & al (2011) found that ants and termites played a similar role in warmer and drier habitats. In a field experiment, they recently showed that ants and termites increased wheat yield by 36% from increased soil water infiltration due to their tunnels and improved soil nitrogen content.

Most people cringe however at the first sign of termites near human habitats. A termite colony’s indifference to the source of cellulose will often lead it to nearby crops, farms and buildings with devastating consequences. The Arabian Peninsula faces the same challenges as any other region of the world with regards to termites. Although Cowey (1989) mentions thirty-three termite species recorded from the Arabian Peninsula, with the greatest diversity occurring in the mountainous south-west, Kaakeh (2005) instead limits the species count to twenty-two. In the regions of the Arabian Peninsula near the Persian Gulf, subterranean Anacanthotermes termite species predominate where at least some proportion of earth is clay and groundwater sufficient to support sparse vegetation. The species feed largely on dry grass and other vegetable debris, but damage to rural buildings, soft timbers, palm thatch and mud bricks (which contain straw) has often been reported. As discussed in Faragalla (1983), traditional houses, mosques and shops in Saudi Arabia were built of mud bricks with local timber, date palm trees and leaves used for ceilings, doors and even posts for farm fences. Mats made of straw and crop stubble were used to cover floors in old houses and mosques, predisposing them to termite attack. Other mentioned targets in the literature include telephone poles, railway ties, furniture and green crops. As suggested in Faragalla, and later in Kaakeh (2005), the problem has been compounded in recent years in response to marginal land use changes for expanded agriculture and urban development which, associated with increased irrigation, encourages the formation of termite-friendly habitats. In addition, the appetite for wood imports for buildings, furniture and other construction is growing in response to the steady increase in population and the improvement in the standards of living in the UAE and other Arab Gulf countries, thus increasing the cellulose offer.

Damages to crops and buildings in Saudi Arabia in the early 1980s reached proportions which triggered government funded research in the field (Badawi, Al-Kady & Faragalla 1986a, and 1986b). Badawi & al (1983) previously evaluated the effectiveness of different chemical preservatives (Chlordane, bitumen, Permethrin, Sumithion and Sevin) on local Saudi woods (Ar-ar, Athl, Sidir, Hamat and Talh) against subterranean termite degradation. Badawi, Faragalla & Dabbour (1984) then investigated the natural resistance to termites of imported wood commonly found in Saudi markets. Beech and spruce were found perishable to termites within periods as short as four months, while apitong and pine showed little damage (3 to 13%, respectively). Untreated mahogany samples showed no sign of attack. Finally, Badawi, Faragalla & Dabbour (1985) compared the relative protective effectiveness of chemical preservatives on imported wood. Chlordane, Aldrin, Dieldrin and Sumicidin were found to be effective after a year, even at low concentrations.

Kaakeh (2005) investigated the survival and feeding behaviour of Anacanthotermes ochraceus (subterranean termites prevalent in the UAE and elsewhere along the Persian Gulf) in a forced feeding
bioassay in response to samples from 10 local timber and 36 imported timber easily found in UAE construction markets. Among the imported species, the following were from North America: hard and soft maple, Atlantic white cedar, yellow poplar, red and white oak, redwood and western hemlock. All local woods tested were classified as \textit{susceptible} to \textit{very susceptible}. While redwood was classified \textit{highly resistant} (no damage, all termites died within 4 weeks), only the following North America species were classified as \textit{moderately to slightly resistant}: Atlantic white cedar, red and white oak and western hemlock. Maple and yellow poplar were designated as \textit{susceptible} to termite damage. The author recommended avoiding \textit{susceptible} to \textit{very susceptible} species for constructional purposes, unless treated chemically.

In 2011, the Conservation Department of the Abu Dhabi Authority for Culture and Heritage announced the development of a specific research program to address termite infestation\textsuperscript{8}. Several historic buildings in the region, without having a wood-frame structure per se, do have many wooden elements such as doors, windows or roof beams, and are increasingly becoming the target of termite infestations.

Faragalla (1983) mentions that, at the time, the Saudi Ministry of Housing began requiring certification for treatment against termites in new construction. It has not been possible to validate if such requirements remain. For Canadian wood exporters, it may be unclear what the next steps should be.

The Canadian Wood Council (2001) recommends taking necessary precautionary measures, regardless of the building size or construction type, in areas where there is a risk of termite infestation. Experts today agree that the most efficient strategy to control subterranean termites is through prevention, education, and by eliminating conditions contributing to termite infestations. Research conducted jointly by FPInnovations (Forintek Division), the College of Tropical Agriculture & Human Resources of the University of Hawaii at Manoa and the Research Institute for Sustainable Humanosphere at Kyoto University, has led to the development of effective control methods in the field of termite prevention. Empirical data validating the effectiveness of various wood treatments tested in various climatic conditions is available (Morris, Grace & Tsunoda 2011 and 2009; AWPA 2009; Wang & al 2007; Tsunoda & al 2006; Grace 2006; Lake & McIntyre; Grace & al 2004; Tsunoda & al 2002; Morris & Ingram 2001; Grace & Yates 1999).

Forintek produced a complete survey of termite control methods and formulated an approach on design, construction and maintenance process. The 6-S strategy (Morris 2000) is a concept originally developed in agriculture and transferred to termite control in buildings, and includes:

- **Suppression**
  - \textit{Measures intended to reduce and eventually eradicate termites from infested materials in a designated area}

- **Site Management**
  - \textit{Careful site preparation and clean-up can do much to discourage the colonization of a new or existing building site by termites}

- **Soil Barriers**
  - \textit{Use of physical sand, stone barriers or chemical barriers}

- **Proper Slab and Foundation Details**

\textsuperscript{8} http://www.thenational.ae/featured-content/latest/termite-threat-to-al-ains-historic-buildings
- Foundation walls and slabs designed to inhibit the entry of termites into buildings, and to facilitate inspection for shelter tubes
  - Structural Protection
    - Use of preservative-treated framing according to local building codes
  - Surveillance and Remediation
    - Baiting, fumigation or heat treatment

Ten-year results of field exposure in Hawaii and Kagoshima, Japan, in relatively aggressive termite feeding situations and in Kincardine, Ontario, show that borate treatments, as well as ACZA treatments, can provide long-term protection from termite attack to structural lumber. For outdoor applications where water exposure is likely, wood treated with ACQ, ACZA or CA is favoured. For structural components of a house in a termite infested zone, borate-treated wood is usually preferred. Borate is a benign chemical, non-toxic to humans, yet highly effective against termites. However, borate-treated wood cannot be used outdoors, as the chemical protection may eventually disappear due to water solubility. Recommended next steps are to determine regulatory requirements, and favoured treatments if so required.
Regulatory Framework

Even if Canadian wood-based construction systems and envelope assemblies were well designed in response to the climate and insect fauna of the Arabian Peninsula, and theoretically performed well in comparison to local construction practices (e.g. masonry units), there remains a set of potential barriers to increased Canadian exports to the area: building code and regulations.

In addition to the traditional building code objectives that hinder the widespread use of wood-based construction systems, namely fire-safety (an important topic which isn’t covered at all in this document), there are a growing number of new code objectives that either have been recently integrated in building codes of various Arab Gulf states, or are in the process of being adopted. Energy conservation and peak demand management appear to be the most prevalent in recent years (Hannah 2011, Assem & Al-Mumin 2010; Radhi 2009b; Radhi, Eltrapolsi & Sharples 2009). As in many parts of the world, building codes are highly regional, e.g. code requirements differ between Dubai and Abu Dhabi, although both are within the UAE. Renowned to be highly cryptic for many, building codes are subject to interpretation without proper professional training and experience and/or guidance from local code authorities. Determining regulatory barriers, as well as opportunities, with some degree of confidence requires not only a thorough analysis of written code requirements per region of interest, it requires some interpretative validation by local professionals, builders and code officials (e.g. through interviews, focus groups, case studies). No manufacturer or professional should be satisfied with a 90% confidence assessment that a given structural solution or building envelope design is compliant with a given building code, with the risk of falling prey to an end-of-the-process refusal by local code officials.

Without knowledge of selected regions, targeted building types and morphology, considered construction systems and assemblies, etc., it is virtually impossible to clearly identify Middle East regulatory obstacles for Canadian wood exporters, currently or in the near future. Nonetheless, the following is a modest overview of Dubai’s recent Green Building Regulations & Specifications (Government of Dubai 2011), which according to Najeeb Zaafrani, secretary-general and CEO of the Dubai Supreme Energy Council (SEC), will become mandatory for the public and private sector from 2014 onwards. One should consider this as a simple illustration of the questions and potential answers with regards to the increased integration of wood in Middle East architecture. Table 8 summarizes the prescriptive thermal performance requirements for building envelope assemblies. Table 9 provides a short list of selected requirements from Dubai’s Green Building Regulations & Specifications, other than those in Table 8. The left column presents the verbatim requirement, while the right column holds related comments.

Table 8 - Prescriptive thermal performance requirements for building envelope assemblies, taken from Dubai’s Green Building Regulations & Specifications (Government of Dubai, 2011). Assembly Usi values (thermal conductance, SI) are expressed in W/m².K; Rsi values (thermal resistance, SI) in m².K/W, and R values (thermal resistance, IP) in Btu/h.ft².°F

<table>
<thead>
<tr>
<th>Element</th>
<th>Usi</th>
<th>Rsi</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof</td>
<td>0.30</td>
<td>3.33</td>
<td>18.93</td>
</tr>
<tr>
<td>Wall</td>
<td>0.57</td>
<td>1.75</td>
<td>9.96</td>
</tr>
<tr>
<td>Fenestration</td>
<td>2.1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 9 – Additional requirements from Dubai’s Green Building Regulations & Specifications (Government of Dubai, 2011)

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Timber certification is a process that results in a certificate (written statement) attesting to the origin of wood raw material and its status and/or qualifications, often following validation by an independent third party. Certification is intended to allow participants to measure their forest management practices against standards and to demonstrate compliance with those standards. Timber certification generally includes two main components: certification of sustainability of forest management (which occurs in the country of origin) and product certification (which covers the supply chain of domestic and export markets). For all new buildings, at least twenty five percent (25%) by volume of the timber and timber-based products used during construction and permanently installed in the building must be from certified / accredited sources approved by Dubai Municipality.</td>
<td>Unique to wood-based construction, and very important to note for wood exporters – at least to determine clearly what accredited sources are approved by the Dubai Municipal Government.</td>
</tr>
<tr>
<td>For all new buildings, building materials available regionally must comprise at least five percent (5%) of the total volume of materials used in the construction of the building.</td>
<td>Not unique to wood-based construction, but important to consider if an overwhelming proportion of materials are to come from Canada or abroad.</td>
</tr>
<tr>
<td>For all new buildings, composite wood products used in the interior of the building must not contain added urea-formaldehyde resins.</td>
<td>Unique to wood-based construction, and very important to note for wood exporters</td>
</tr>
<tr>
<td>All opaque external roofing surfaces must comply with a minimum Roof Solar Reflective Index (SRI) value according to Table 304.01(1) for a minimum of seventy five percent (75%) of the roof area</td>
<td>Not unique to wood-based construction, but important to note for exporters.</td>
</tr>
<tr>
<td>For all new buildings, at least seventy five percent (75%) of the area of externally painted walls must have a minimum Light Reflective Value of forty-five percent (45%).</td>
<td>Not unique to wood-based construction, but important to note for exporters, especially if wood cladding is considered.</td>
</tr>
<tr>
<td>For all buildings, including new applications in existing buildings, all paints and coatings used in the building should not exceed allowed limits of Volatile Organic Compound (VOC), these paints and coatings must be accredited/certified from Dubai Central Lab or any source approved by Dubai Municipality. For all buildings, including new applications in existing buildings, all adhesives, adhesive bonding primers, adhesive primers, sealants and sealant primers used in the building should not exceed allowed limits of Volatile Organic Compound (VOC), these materials must be accredited/certified from Dubai Central Lab or any source approved by Dubai Municipality.</td>
<td>Not unique to wood-based construction, but important to note for wood exporters with regards to wood finishes - at least to determine clearly what accredited sources are approved by the Dubai Municipal Government.</td>
</tr>
</tbody>
</table>

The prescriptive requirements in Table 8 will apply to all new buildings, new extensions to existing buildings as well as major renovations, regardless of the expected occupancy (e.g. small scale residential versus office buildings). There are exceptions to its application, including heritage buildings, (very) large
scale complexes and temporary buildings (i.e. to be removed within two years after construction, e.g. temporary worker housing). Well-insulated, wood-framed construction familiar to Canadian professionals and builders comply with these levels without difficulty. For instance, R20+ flat roofs (e.g. continuous on-deck rigid insulation) are standard practice for new commercial and institutional buildings in Canada, while a 2”x6” @16”oc wood-framed wall (full cavity insulation and R5 continuous insulation) offers an effective[^1] ~R21. So at least initially, well-insulated wood-framed construction should compare well against the competition (e.g. CMU-based, aluminium-framed curtain wall). Note that there are no indications however on how such U-values are to be determined (i.e. no references to testing standards or calculation procedures), leaving some room for gamesmanship, unless the authority having jurisdiction (e.g. City of Dubai) offers guidance to this end in other documents. For instance, it is unknown if thermal conductances and resistances in Table 9 refer to effective or nominal values. Similarly, it is unclear if required Usi values for windows take into account framing effects (as per North American standards), or simply represent centre-of-glass values; an important distinction for manufacturers.

Like many of the world’s energy codes, Dubai’s Green Building Regulations & Specifications allows as an alternative to relying strictly on prescriptive requirements, a performance-based compliance route through the use of building energy simulation: compliance is demonstrated if the annual energy consumption of the proposed building is equal or lower to the annual energy consumption of the reference building. This mechanism allows, for instance, the use of curtain wall spandrel panels (~R5) for new construction as long as one or more compensatory measures (e.g. reduced lighting power densities, more efficient fenestration, better cooling COPs) are introduced to offset the negative energy impact of the spandrel panels. A corollary is that high-performance wood-framed construction (e.g. an effective R21 wall) could be considered as a compensatory measure in many cases (i.e. contrary to the competition, well-insulated wood-framed construction could be part of the solution rather than part of the problem to fix). High-level, published material could be prepared to illustrate such advantages to Persian Gulf professionals and authorities.

[^1]: Effective, in contrast to nominal, takes into consideration thermal bridging from structural components such as wood or metal studs.
Summary

Although for centuries, wood timbers have been used for structural purposes (ex. roofs) and essential architectural elements such as windows, doors, shutters and screens in the Arab World, wood-framed building envelopes are somewhat of a rare occurrence in Gulf countries. Expanding the use of wood in such ways, does open the floor to legitimate questions on durability, robustness and safety (structural, fire), that need to be addressed.

Climate analysis indicates that Persian Gulf coastal locations of the Arabian Peninsula (< 25 km away from the coastline) are very hot and humid, similar to Orlando yet with greater daily variability and extremes, while inland locations are very hot and dry, similar to Phoenix yet again with greater variability and extremes. Building envelope assemblies well-suited for either Orlando or Phoenix are likely good candidates for the Middle East, requiring either minimal adaptations or some degree of robustness appropriate for either Arabian Peninsula extremes.

Beyond climate analysis, little to no scientific material on the specific topic of wood-based building envelope assemblies and structures in the Middle East has been published to date. The literature is rich nonetheless with well-developed bodies of scientific knowledge that may be qualified as peripheral to the principal topic. There is a wealth of contextual information that would, in turn, be useful for wood exporters, such as what the competition is, their respective issues and what innovations are on the horizon. This in turn provides a basis of comparison when establishing the pros and cons of adopting wood-based systems. The literature also provides information on building typologies expected to be built (e.g. multi-unit residential, schools, offices), their morphology (e.g. building heights, aspect ratios, fenestration), assumed operating conditions, standard HVAC practices, etc. Along with knowledge of regional climate, this information is critical in establishing an appropriate contextual framework from which the multi-criteria performance of wood-based systems is to be evaluated.

Increasing organic content in building envelope assemblies (e.g. wood framing, cellulose insulation, wood-based sheathing) would still raise concerns on durability, moisture management, airtightness, workmanship and termite prevention. As the literature only provides partial answers to these questions, there appears to be a clear need for Canadian wood exporters and associations to define and undertake a scientific research programme, complemented with field inquiries, to counter this knowledge gap. As there is a substantial body of scientific and empirical knowledge of which wood-based assemblies and systems work well in US hot-dry (e.g. Phoenix) and hot-humid (e.g. Orlando) climates, such concepts and designs may constitute a good starting point from which to fine-tune the design of wood-based assemblies to suit the climate extremes of the Middle East.

The recommended next steps would be to narrow down regions of interest, targeted building types and scale, considered construction systems and assemblies, etc., as to better circumscribe the scope of subsequent analyses, such as dynamic hygrothermal assessments as a function of indoor and outdoor psychrometric states, determining regulatory barriers as a function of region and building type and scale, etc. Determining regulatory requirements with some degree of confidence entails not only a thorough analysis of relevant building code articles per region of interest, it requires validation by local professionals, builders and code officials (e.g. through interviews, focus groups, case studies).
References


AWPA (2009) Standard method for the evaluation of preservative treatments for lumber and timbers against subterranean termites in above ground protected applications (UC1 and UC2), American Wood Protection Association: Birmingham

Badawi AI, Al-Kady H & Faragalla AA (1986a) Termites (Isoptera) of Saudi Arabia, their hosts and geographical distribution, *Journal of Applied Entomology* 101(1-5):413-420


de Villiers MP (2010) Predicting the development of weather phenomena that influence aviation at Abu Dhabi International Airport, PhD thesis, University of Pretoria


Evans TA, Dawes TZ, Ward PR & Lo N (2011) Ants and termites increase crop yield in a dry climate, Nature Communications 2(262)


Additional Reading

The following are unreferenced publications that deal with similar topics yet not directly pertaining to the Arab Gulf countries. Subsequent research efforts may find such publications useful.


