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Buildings & Climate Change: Methodology and Areas for Further Research

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Abstract

This white paper presents an introduction to the current work being carried out for the upgrading of the Infrastructure Planning Support System to incorporate an holistic approach to the specific impacts of climate change on buildings. The approach builds upon previous work associated with the DUCC effort that emphasized the impact of climate change on roads. The paper illustrates how climate change can affect both wood-based structures as well as masonry-based structures. Issues including the potential effects on exterior siding, ventilation systems, roofing, and drainage systems as well as structural effects are considered in the expanded analysis.

Keywords: Climate change; infrastructure vulnerability; infrastructure maintenance

JEL Classification: Q54, O44, O55

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1.0 - Introduction

In order to create lasting structures, especially where a focus on green and sustainable building practices are being considered, the design and adaptation of new buildings needs to consider and anticipate a diverse range of potential future climate scenarios. The consideration of climate change and future scenarios has been pursued and applied to a broad range of development issues. Although studies have acknowledged the need for greater awareness and incorporation of potential climate change impacts on infrastructure, few have approached the issue with methodologies that can produce tangible, replicable results to be of use by policy and decision makers.

The existing literature related to climate change adaptation in the infrastructure sector is primarily qualitative in nature with an emphasis on broad recommendations and warnings. These studies are primarily based on general weather studies, or focus on qualitative predictions. Research completed by the Transportation Research Board in the United States, the Scottish Executives, and Austroads in Australia are notable efforts in this regard (TRB 2008; Galbraith et al 2005; AUSTROADS 2004). Within these reports, the authors compare weather-related disasters and their perceived severity with predicted climate change impacts. Further studies have advocated determining specific impacts of temperature, rain, snow and ice, wind, fog, and coastal flooding on roads (CCSP 2006). Additional studies have been undertaken in areas where specific climate change concerns threaten infrastructure that is unique to that locale.

The limitation of existing impact studies on infrastructure is that they either focus on a narrow potential impact of climate change, or the studies fail to provide specific estimates of cost or damages that may result from potential climate change scenarios. In response to this gap in the climate change literature, the authors have been actively engaged in developing specific estimates of climate change impacts on infrastructure elements. Chinowsky et al (2011a) document the potential cost impacts of climate change on road infrastructure in ten countries that are geographically and economically diverse. The study illustrates both the potential real costs that countries may incur due to climate change scenarios as well as the potential opportunity costs of diverting infrastructure resources to climate change adaptation. Additionally, other authors have extended this response methodology to determine the potential impacts from climate change on bridges (Stratus 2010) and roads in northern climates (Industrial Economics 2010).

An EACC Study (World Bank 2010) completed in 2009, estimated that urban housing costs could increase between $23.3 billion (2005 USD) and $41.1 billion per year in the period 2010-2050 because of climate change impacts. This estimation does not include considerations such as slum areas. Buildings are an essential component of the built environment, the economy, and the daily lives in any area. A failure to properly incorporate climate change considerations could result in costly impacts including sick building syndrome, roof and drainage issues, cladding and exterior façade deterioration, and issues with the foundation of buildings, among many others. Additionally, a proactive approach to understanding and addressing many of these issues may present an opportunity for buildings to be enhanced with alternative, green technologies which serve to reduce vulnerability to climate change impacts and reduce emissions and other negative environmental impacts.

This white paper presents an introduction to the current work being carried out for the upgrading of the Infrastructure Planning Support System to incorporate an holistic approach to the specific impacts of climate change on buildings. The approach introduced in this paper builds upon previous work associated with the DUCC effort that emphasized the impact of climate change on roads (Chinowsky and Arndt 2012). From this basis, this paper details the current level of analysis for different types of buildings and discusses opportunities to improve this research, including additional adaptation options.

2.0 - How to Approach Climate Change and Buildings Analysis: Identifying Critical Impacts

This section provides a comprehensive overview of the climate change impacts that may affect buildings and the building components that are vulnerable to climate change impacts. While the current analysis does not capture all of these elements, it is critical to understand the holistic nature and varying degrees of impact that may be relevant to each region and should be considered in conjunction with the methodology and analysis discussed in section three.

2.1 – Relevant Climate Change Impacts

Understanding the impacts of climate change on buildings can be estimated through analyzing both the potential future climate changes and understanding the impacts of climate on buildings. Seven factors of climate change that affect buildings include:

1. Increased soil drying will affect water tables and could affect foundations in clay soils
2. Maximum and minimum changes in temperature will affect heating, cooling and air conditioning (HVAC) costs. Frequency of cycling through freezing point will affect durability of materials such as brick and stone (*see below*). Daily maximum and minimum will affect thermal air movement. Sick Building Syndrome must be carefully analysed to minimize the impact of climate change on health and environmental safety.
3. An increase in relative humidity will affect condensation and associated damage or mould growth (*see below*).
4. Precipitation increase and decrease will affect water tables (foundations and basements); cleaning costs will be increased in winter, with associated redecoration requirements; durability and risk of water ingress will be increased by combination of greater precipitation and associated gales.
5. An increase in the occurrence of gales will result in a greater need for weather tightness in buildings, with an increased risk of: water ingress; effectiveness of air conditioning; energy use; and risk of roof failures.
6. Increased radiation will result in the need for greater solar glare control in buildings.
7. Increased cloud cover in the winter months will increase the need for electric lighting, whilst reduced cloud cover in the summer may reduce the need for electric lighting for

certain buildings (Graves & Phillipson 2000).

2.2 – Building Components and Sub-Structure Vulnerabilities

Some of the critical potential impacts of climate change on components and sub-structures and whole buildings (with a focus on maintenance) have been identified in the literature as follows:

Whole Buildings:

1. Potential increase in cleaning costs due to wind, gales, relative humidity and precipitation
2. Construction costs and build time may increase/decrease depending on season and region
3. Increased risk of failures of timber framed construction due to potential increase in relative humidity, depending on design.

Sub-structures:

1. Increased fixing cost and risk of failures in roofs due to gales, wind and precipitation
2. Increased risk of damage to foundations and sub-structure concrete due to subsoil water.
3. Increased risk of heave or subsidence in basements/sub-structures due to water ingress, consequential damage to finishes and stored items including plant.
4. Increased risk of cracking in structure/cladding/renders/roofing membranes due to different in thermal or moisture movements.

Components:

1. The life span of most materials will be reduced by an increased salt spray zone in marine areas (*see below*).
2. Plastics will have a reduced life expectancy due to increased radiation (*see below*).
3. Increased risk of failure of sealants due to different thermal or moisture movements
4. Complex mechanical and electrical service systems will have reduced life or reliability if increased temperature is not controlled; this may also have health and safety implications.
5. There may be savings in winter running costs of HVAC systems with decreased heating requirements but there will be a need to upgrade airtightness with increased cooling requirements in the summer months
6. Lighting systems will need to be adapted to meet the needs of increased cloud, which will reduce natural light and increased radiation which may increase the need for glare control (Graves & Phillipson 2000).

Many of the impacts highlighted above would only affect the maintenance requirements of existing buildings. As maintenance is a factor for calculating whole life/life cycle costs, all impacts listed are relevant to some degree.

2.3 - Building Materials

In addition to the components listed above, two important additional considerations are: the impact that climate change may have on performance of buildings and the impact that climate change may have on building materials. Material components are a key area for concern as any approach to mitigation is complicated by the fact that climate change may affect the degradation and durability of different building materials in opposite directions. Biodegradation, salt damage, freeze-thaw damage and increased solar radiation are considered below:

Freeze -Thaw Damage

This is a major concern for brick and natural stone masonry and its severity will depend on the expected increase/decrease of number of freeze-thaw cycles. Materials may be wetter at the onset of frost due to higher precipitation, with a possible increase in freeze-thaw damage. Enhancing the frost resistance of masonry, especially repointing mortars by using air entraining agents or gap graded sand (Van Hees et al 2001) is believed to be an appropriate adaptation approach.

Biodegradation and Biocolonization

The combined effect of higher temperature and higher precipitation is likely to speed up biocolonisation and increase the effects if biodeterioration and biodegradation of stonework, (organic) coatings and timber.

Possible adaptation measures may range from the development of new, innovative materials with slow controlled release of biocides to selection of currently available and more sustainable materials. Materials with low water retention will be less prone to biocolonisation than those with higher water retention, as a result the use of coarsely porous building materials may be an appropriate adaptation measure. The use of water repellent treatments has been suggested (Adan 2003), however this may result in further damage due to salts decay and/or increased solar radiation which is likely to speed up the degradation of water repellent agents (Nijland et al 2009).

Salt damage

It is possible that salt damage to fired clay brick and natural stone masonry may increase, and will particularly impact on historic building, which by their nature have been exposed to the elements for longer. Besides higher temperatures, which may result in faster evaporation, water penetration of facades is expected to be deeper, potentially dissolving more salts that may be transported and accumulated, resulting in irreparable damage to the stone/brickwork. To what extent higher temperatures and higher precipitation will result in more relative humidity cycles in which the equilibrium relative humidity of water-soluble salts is crossed, is yet unclear (Nijland et al, 2009). Research has demonstrated that only a small increase may have severe effects on salt damage to porous building materials (Lubelli 2006; Koster et al. 2008).

Salt transporting or salt accumulating plasters or bricks with a pore structure favouring salt crystallisation at the surface (efflorescence) rather than behind the surface (crypo-efflorescence) may be appropriate as an adaption approach (Nijland et al. 2009).

Increased solar radiation

Increases in the level of solar radiation, in addition to its impact on the lifespan of building materials, could lead to overheating which might increase the need for cooling, particularly at night. Higher levels of solar radiation would also lead to dark materials directly exposed to the sun absorbing more heat and hence reaching higher temperatures. Differential thermal expansion could therefore become more of a problem (Ross et al. 2007).

It is possible that this will be compensated for by the development of advanced light-stabilising technologies, based on both conventional and improved photostabiliser systems (Andrady et al 2003).

Masonry

Few other materials can match the durability characteristics of masonry, when correctly designed and constructed and with due consideration paid to the distinctive features of the material.
Masonry defects can be understood as a function of local climate impact, choice of materials and compatible composition of materials, design and quality of workmanship. The pursuit of durable masonry structures requires an optimal realisation of the climatic exposure and the special features of the brickwork. Well-functioning methods and solutions for a typical sheltered inland climate are not necessarily appropriate in a more exposed type of climate. Driving rain and frost action are the principal climatic challenges to be considered in the pursuit of high-performance masonry structures. Shrinkage and thermal movement, the most frequent defect category, dominate independent of the climatic impact. It is a defect category more dependent on the design and construction of masonry structures. First call workmanship and movement joints and the sliding layer (DPC) being carefully considered throughout the construction process.

Small errors or mistakes can bring about major and often irreparable defects or damage to masonry structures. There is a need for guidelines to ensure local climate adaptation (Kvande & Liso 2009).

3.0 - IPSS Approach

As indicated above, the potential impact of climate change on buildings can be varied and extensive. The current IPSS approach isolates these potential impacts to ones that have been detailed in existing research as well as ones that have a mitigation path that can be accomplished through focused adaptation. Specifically, the areas of exterior cladding impact, roofing impact including drainage, and air flow impact including the mitigation of potential building contaminants are the focus of the IPSS expansion accomplished within the current research effort. This section details how the stressor-response approach adopted for the underlying IPSS system has been adapted for the expansion into building impacts.

The overall approach adopted in the IPSS system involves three steps of analysis: climate model projections, existing building stock estimation (and optional future growth scenarios), and the analysis of climate change impact on buildings.

3.1 – Climate Model Projections

The stressor-response approach to incorporating climate model projections into the IPSS system has been previously documented by the authors as both an approach and an application (Chinowsky and Arndt 2012; Chinowsky et al 2012). As a summary, the current methodology employs the HFD approach developed by Schlosser et al (2011). In this approach, 17 IPCC 4th Assessment (AR4) climate models are used as a basis for generating a suite of climate scenarios. To address the uncertainty associated with climate scenario projection including downscaling, economic, and policy issues, the HFD approach incorporates a set of 400 factors which are varied over the 17 climate models. The combination of these elements provides 6,800 discrete climate scenarios for each overall policy limit on climate change. The set of scenarios is shown by Schlosser to provide an illustration of the likelihood that climate change impacts will occur in a given global zone.

For the current study, an unconstrained policy is modeled to focus on the least restrictive projection of climate change scenarios. From this pool of 6,800 possible scenarios, a statistical sampling was employed to extract a set of 425 representative climate scenarios. The result of this extraction is a pool of 425 scenarios that are considered equally plausible outcomes from the unconstrained policy. Through the use of the large diversity of climate scenarios, the current study uses a broad basis for developing a set of potential climate impacts rather than focusing on a limited group of results. The concept behind this adoption is that a greater number of scenarios will provide decision makers with a more comprehensive perspective on possible outcomes.

3.2 – Existing Building Stock: Estimations

The methodology for incorporating building stocks into the IPSS system incorporates a dual approach to building stock quantification. The first and more desired approach is to gather actual building stock data from sources such as Ministries and NGOs that track actual data for building stocks in specific countries. However, these accurate counts are not always available. In these circumstances, a methodology is required to estimate the number of buildings based upon individual country characteristics and population. An initial approach to such a methodology was developed for IPSS for a previous study conducted by the Asian Development Bank. In both approaches, the building stock is divided into urban and rural categories for: schools (primary and secondary buildings), public administrative buildings, hospitals, standalone homes, small apartment buildings, and large apartment buildings.

In the scenario where actual data is not available, estimates were generated for each country using the data inputs below. For housing estimates, the population falling below the official poverty line (or $2/day, whichever is greater) was not included in this analysis.

The input data for determination of building stock (country-specific data):

- ***Schools***: number of primary and secondary aged children, enrolment rates; average number of school buildings per 1,000 students, urban and rural numbers.
- ***Public Administrative Buildings***: Number of administrative levels (assumed 1 administrative building per geographical administrative unit)
- ***Hospitals***: Total population; number of hospital beds per 1,000 population; average number of beds per hospital, urban and rural
- ***Rural Homes***: Total rural population ((total population * percent rural) – population living below poverty line or $2/day); average household size, rural; average house size, rural.
- ***Urban Homes***: Total urban population ((total population * percent urban) – population living below poverty line or $2/day or slum population, if available); average urban household size; percent of population living in apartment complexes

The conclusion of this process provides a building stock inventory from which the IPSS system can be used to estimate the total cost impact of climate change within a given country and its sub-administrative units.

3.3 – Analysis of Climate Impact on Building Stock

The existing IPSS Analysis for climate change impacts on building stock is based upon the differentiation between two main types of buildings: wood and non-wood structures.

3.3.1 - Wooden Buildings, Scheffer Approach

Wooden buildings are assumed based on existing data to comprise the majority of rural housing stock and rural schools. The impact of changing climate, especially increased precipitation or temperature, will affect the rate of decay for these structures. The IPSS method employs the Scheffer Method (Scheffer 1971), a recognized method for determining wood deterioration based on climate. The Scheffer Index (SI) was introduced by Theodore Scheffer to compare the effects of climate on untreated wooden structures throughout the United States. Based on the U.S. Weather Bureau Summaries, climate information was collected for several sites and an index was developed to estimate the relative potential of decay. Based upon Scheffer's classification, higher temperature and precipitation climates are considered 'more severe' because they lead to a quicker degradation than dryer, lower temperature climates. The SI calculates a 'time to failure' and estimated degradation rates. The formula for the index is provided in Formula 1.

FORMULA 1:
Scheffer Climate Index =
$\square - 2 * \square - 316.7$

Where:
The SCI = Summation of months in a given year from January to December.
T = mean monthly temperature (Celsius)
D = mean number of days in the month with >0.25 mm precipitation

The Scheffer Index is an annual summation of the monthly climatic data for a particular region. Each year is given an SI, usually between approximately 0 and 120. The higher the SCI, the greater the time until decay causes failure in the structure. In the current study, a "Historic SI" is established based on current climatic data for each region. Utilizing the projected climate changes in precipitation and temperature, a "Climate Change SI" is established for a given year. For example, to understand the climate change effects on existing building stock in 2050, a Historic SI is established based on 2010 climate data. Then a Climate Change SI is established based on the projected temperature and precipitation data using Formula 1. The two Indexes are compared. Each SI can be translated into a 'time to failure' by Formula 2.

FORMULA 2:

$$\text{Time to Failure (TF)} = 80 / \text{Scheffer Index (SI)}$$

Where:
TF = estimated time to failure (where structure must be replaced or significant maintenance must be performed) in years

Based upon Scheffer's published calculations based on the United States, this provides an approximate time to failure for a wooden structure under certain climatic conditions.

To minimize minimal fluctuations in climate data, impact costs are only analyzed if the Historic SI and Climate Change SI are different by greater than "5". This represents one regional change of climate of the overall 8 regions defined in the climate analysis. If there is a Historic SI and Climate Change SI difference of 5 or greater, a degradation rate is calculated and the estimated loss of life is determined. Costs are then applied as a percentage of total construction cost multiplied by the estimated percentage of life lost. See Formula 3 for the loss of life calculation.

FORMULA 3:

$$\text{IFF: } (\text{Historic TF}) - (\text{Climate Change TF}) > 5,$$

$$\text{Loss of Life (LOL)\%} = (\text{Historic TF}) - (\text{Climate Change TF}) / (\text{Historic TF})$$

Where:
LOL is the percentage of the structure's historic lifespan that has been reduced based upon climate change impacts

Because the formula provides an estimate for degradation based on 'average' climates (where the typical time to failure is between 30 and 50 years), the SI used in this analysis is adjusted to account for more severe climates. A base time to failure of 15 years is used. This means that if the SI predicts a time to failure of 15 years or less, 15 years is used. This reflects the fact that building codes or local standards will provide a minimum level of required lifespan in climates where even severe temperatures are expected.

Climate change costs are then estimated as the loss of life to structures based upon the change in climate impacts of precipitation and temperature. Costs are then applied based on the construction cost per square meter times the average size of a particular building type.

FORMULA 4:

$$\text{Climate Change Cost} = \%LOL * \text{Construction Cost}$$

For example, if it is projected that there is a 15% loss of lifespan due to projected climate change impacts in 2030 and the construction cost per square meter $500, then we have a climate change cost of $25 per square meter. If the average size of the structure is 160 square meters, then the total climate change cost per structure in that region is $4,000.

3.3.2 - Other Buildings, MEWS Approach

The MEWS Methodology utilizes the MEWS Index for classifying weather impacts on buildings with exterior cladding made of non-wooden materials, including steel, masonry, and concrete (Cornick et al 2002). These building materials are more resistant to climate impacts. Thus, the authors evaluated climate impacts on the HVAC (Heating, ventilation and air conditioning) system with the assumption that the impact on external cladding will be minimal due to climate effects. A threshold approach is used to determine if the changes in climate precipitate a significant rise in humidity, occurring from changes in temperature and/or precipitation. If the humidity rises above a threshold, the building codes for HVAC load mandate a mandatory upgrade of the system to handle airflow for health of the occupants. The MEWS index is calculated for a baseline (current) climate and future climate. If the threshold is passed, a cost is applied based on the cost per square meter of upgrading HVAC for a specific building type.

The MEWS Index is an approach adopted by the MEWS consortium and is fully documented by Cornick et al (2002). It utilizes a Moisture Index, defined by a Wetting Index (WI) and Drying Index (DI) to calculate the amount of moisture that a building will be subjected to under varying climate conditions. Using this Moisture Index as a basis, the MEWS Index defines the climate region that a structure exists within based on the conditions that it is subjected to during given periods of time. This Index is then normalized to provide an indication of the changes in precipitation or temperature that are sufficient enough to change the climate condition under which the structure was designed. In these cases, a threshold is considered to be crossed and adaptive action is required. In the case of this study, that action is to upgrade the HVAC system.

The MEWS Methodology utilizes a threshold approach of classifying climates into five thresholds:

Severe	High	Moderate	Limited	Low
>1.0	0.9 -1.0	0.8 – 0.9	0.7 – 0.8	<0.7

Table 1: MEWS climate threshold classifications

For each administrative region, a Historic MEWS Index (HMEWS) and a Climate Change MEWS Index (CCMEWS) are calculated based on the climate information. The HMEWS provides a baseline estimate for the existing HVAC system. If the CCMEWS is one or more thresholds above the HMEWS, mandatory upgrades of the HVAC systems are assumed for health reasons and building code compliance. These costs are assessed as a percentage of total construction cost.

FORMULA 5:

$$\text{Climate Change Cost} = 4.5\% * \text{Construction Cost} * \text{Number of Thresholds Exceeded}$$

Where:

Climate Change Cost = total cost applied to each building

Construction Cost = average cost for construction of a building based on cost per square meter and average size of building

In this analysis, 4.5% is the estimated cost of total construction costs that are directly attributed to HVAC components. This is based on the cost of the system components that would need to be replaced (boilers and fan units) as a percentage of the overall HVAC system which is a percentage of the overall building costs.

3.3.3 - Other Buildings, Roofing Adaptation

A second focus of the building analysis is on the potential damage to roofing materials on flat-roofed (typically public) buildings such as hospitals, schools, emergency, and apartment buildings. For these structures, roofing is designed based on projected amounts of water that will exist on the roof from rain events. Based on these projections, the size of roofing drainage systems is calculated. A failure to adequately size the roofing drain will result in water pooling on the roof. This pooling will result in failure of the roofing material as excessive moisture and standing water will ultimately lead to both material and sealant failure.

This factor is included within the current study based on the design parameter of maximum monthly precipitation in a given location. Where the maximum monthly precipitation is anticipated to increase by more than 10 cms, it is determined that a greater precipitation drainage capacity is required. For adaptation, a larger drainage system is placed on the building with a resulting increase in cost of 0.05% of the construction cost for the Adapt scenario and 0.3% for additional maintenance in the No Adapt scenario. These costs reflect the costs of changing the drainage system within a building and in the case of No Adapt scenarios, the cost of repairing roofing materials that are damaged during precipitation events.

FORMULA 6:

$$\text{Climate Change Cost (Adapt)} = 0.05\% * \text{Construction Cost}$$
$$\text{Climate Change Cost (No Adapt)} = 0.3\% * \text{Construction Cost}$$

Where:

Climate Change Cost = total cost applied to each building

Construction Cost = average cost for construction of a building based on cost per square meter and average size of building

Although precipitation increases can have additional impacts on exterior building components such as windows and doors, the effects on these components are individualized to the building and the conditions in which the building exists. Therefore, these impacts are not included in the current study, but should be considered in areas where increased precipitation is considered a likely event.

4.0 – Conclusion and Next Steps

The approach to determining the climate change impacts on buildings described in this paper represents the initial approach that is being implemented in the IPSS system for application in Southern Africa as part of the DUCC II effort. However, continued refinements are being explored in the system as part of the DUCC II effort. These refinements are detailed as follows:

Scheffer Index – The Scheffer Index is applied to wooden structures identified within a current inventory. The greatest number of these structures is found in rural areas of the countries currently being studied. However, in many parts of the developing world, the income level of families occupying wooden structures places them below the severe poverty line. Rather, the majority of populations in these countries inhabit masonry structures. Therefore, it is being determined if the Scheffer Index should be replaced with the MEWS Index for residential and rural public buildings.

HVAC Thresholds – Currently, the MEWS Index is used to determine if an upgrade in HVAC equipment is required in a building to prevent contaminants from forming in the building. Although this approach is reasonable and valid, specific thresholds are being investigated based on public health research which may better inform the current effort on specific threshold values.
Foundation Impact – The final area being investigated is whether a relationship between flooding and foundation damage can be specifically identified for implementation within the system. This relationship would enhance the analysis of flooding impacts on buildings resulting from increased precipitation runoff.

In summary, the current effort is an evolutionary step forward in analyzing the impact of climate change on infrastructure. The initial version of the IPSS enhancements provides the ability to analyze climate impacts on buildings. However, additional enhancements are currently being explored and implemented to allow a robust analysis of impacts in South Africa as part of the overall DUCC II effort.

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