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# A Framework for Construction, Maintenance, Function and Policy Adaptations to Build Resilience to Infrastructure Against the Impacts of the Climate Change

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**Abstract.** With global change in climate patterns, the uncertainty of natural hazards also has gone up significantly in the last few years. In the previously published first part of this two phase study, the authors discussed the impacts of climate change-triggered extreme weather events on our infrastructure. That article recommended the need to quickly adapt our engineering, design methods, and materials to not only perform satisfactorily but also to extend design life, reduce carbon footprint of infrastructure activities and improve structural resilience and sustainability. In this second part of the study, the authors propose the adaptations required in construction methods, maintenance strategies, functional adaptation, and revising infrastructure development policies. The authors believe that this paper extends and complements the first part of the study to provide a holistic understanding of the adaptations required for building sustainable and resilient infrastructure for our communities. The two parts of the study collectively provide a complete framework for sustainable infrastructure development that effectively mitigates the impacts of extreme weather events fueled by climate change and promotes sustainable living on our planet.

**Keywords:** Climate Change, Structures, Adaptation, Sustainability, Resilience, Engineering, Construction, Function, Obsolescence, Policy, Infrastructure

## Introduction

The indiscriminate destruction of vegetation, the burning of fossil fuels and the enormous industrial and domestic waste footprint of infrastructure development are known to accelerate the climate change process on our planet. The dangerous consequences of climate change on our weather and the increased occurrence of extreme weather events and its randomness around the world are discussed in detail by the authors in the first part of the study (Jonnalagadda et al., 2023). In that study, the authors proposed various adaptations required in the development of residential infrastructure in order to be able to provide resilience to it as well as to cut carbon footprint of it to improve its sustainability. Detailed adaptations needed to our structural geometries, design methods, design loads and construction materials were recommended. However, infrastructure activities encompass several additional major phases. Construction, Maintenance, Function and Policy making are the four major aspects of infrastructure that were not discussed in the first part of the study due to size limitations on manuscript.

The objective of this second part of the study is to focus on the adaptations required to our construction methods, maintenance methods, functional use and policy making standards in order to improve resilience to our structures against extreme weather events spun by climate change across Earth. It is essential to touch these major aspects of infrastructure building in order to address this problem holistically. While design methods, materials and geometry adaptations to buildings help quite a bit in improving their resilience, the footprint of construction activities is much bigger because a lot of carbon footprint and natural resource utilization happens due to these activities. Also, construction activities indirectly impact many other social and economic aspects of the local area where the activities are taking place. So it is very essential to adapt construction methods to really see the fruits of design and material adaptations. The second major adaptation is about how we are maintaining structures during their intended service life. Maintenance of structures incurs a major percentage of resources as initial construction. In fact, critically important structures with longer life spans often consume multi-fold resources as compared to the original construction.

## Adaptation of Infrastructure

### Construction Adaptation

Construction industry is one of the biggest contributors to carbon footprint and greenhouse gas emissions. Infrastructure is one of the basic requirements of mankind. As such any minor improvements to construction processes and methods can have very significant positive impacts in the cut down of carbon emissions and slowdown climate change. This section discusses the most commonly used construction methods for building residential structures around the world and how little adaptations to their construction can benefit this planet in a big way.

When it comes to construction, there are two most commonly used methods for building structures. One that is built at the final location of the structure, and the other that is built at a manufacturing facility and brought on trucks to the final location and installed. The first method is called in-situ construction and the second one is called manufactured construction. In the concrete world the second method is also referred to as precast construction. The cast-in-place construction is the traditional method and is still very commonly seen across the world. A vast majority of the homes in many countries are still built at site. Be it wooden or concrete home, this is still the preferred method. This is mainly because it has been the way we developed our construction competencies over several centuries. In his study about the challenges of traditional cast-in-place concrete construction, Jonnalagadda and Vemuri (2023a) discussed in detail about its prevalence, short comings and inefficiencies, and the need for actively pursuing precast concrete construction in place of traditional cast-in-place methods. The authors not only discussed economic and social impacts but also the environmental impacts of this age-old type of construction on sustainability of infrastructure. In the subsequent article, Jonnalagadda and Vemuri (2023b) also proposed the various novel construction methods available as replacements for this type of construction. The authors recommend that precast construction, low carbon, self-sufficient and sustainable methods need to replace cast-in-place methods.

Precast construction offers a great opportunity to replace cast-in-place construction methods still used in most parts of the world. Precast concrete construction is efficient, economic low-energy consumption, environmentally friendly and offers building solutions quickly with least interruption to public, traffic and communities. The construction quality produced by precast cannot be matched by cast-in-place methods. Precast beams, girders, columns, walls, slabs, piers and foundations have been successfully used in many countries (PCI Design Handbook, 2017). The applications include every major structure such as multistoried buildings, stadiums, bridges, highways, ports, and architectural panels. Any structure that can be built in-situ can be built precast. Advanced connections of precast members such as beam-column, column or wall to foundation, column-column can be designed for robust performance in seismic locations as well (Cleland & Ghosh, 2012). Combining precast with high performance concretes such as Ultra-High performance concrete (UHPC) or High performance concrete (HPC) has been having major applications in high shear transfer zones (Jonnalagadda & Vemuri, 2023c) such as beam -beam joints and beam-column joints as well as in seismic locations (PCINE, 2014). These construction systems are very efficient, quick to work on, and are expected to have longer lives despite the high fatigue and shear loads they see on a day-to-day basis (Jonnalagadda & Chava, 2023). These solutions not only improve long-term performance and life of the structures but also reduce the maintenance, repair and rehabilitation requirements there by improving the sustainability of the structures significantly. This adaptation from cast-in-place to precast is happening, however various problems stop this adaptation from happening at a fast pace. In advanced countries, mindset of construction industry coupled with legal liabilities to unforeseen accidents is the cause of this slow down. In developing countries, its altogether different set of issues; shortage of engineering expertise, the lack of manufacturing capabilities, the high initial cost of setting up precast fabrication facilities are some of the major culprits. However, adaptation of builders, engineers and owners is the biggest overall constraint for adaptation of construction methods (Jonnalagadda & Vemuri, 2023a). Precast is an excellent method of choice of construction for mass housing units in developing countries with huge populations; these are small single family suites typically with less than 500 square foot area that are produced in large numbers. These are not only affordable but offer a simple living. These units are low on per capita carbon footprint and offer sustainable living choice. High on quality, low on footprint and waste, quick fabrication in plant and ability to be shipped on trucks and erected on site in less than a day, precast offers perfect choice of construction for these small family units.

In cold countries where wood is preferred material of construction of homes, most of the residential houses are built at the site. Typically wooden beams are erected on wooden columns and beam stiffened stucco or plaster walls are erected with roof on purlins and rafters. This method of construction is entirely in-situ (or built in place). The utilization of manufacturing process in building these homes is still at a very low level. Prefabricated or manufactured homes in wood can reduce the material, labor and resource consumption quite significantly. There can be huge reduction in carbon footprint and tree cutting and logging that can be achieved. Manufactured home makers are more likely to use novel materials such as composites instead of just natural wood from trees there by promoting greener methods. Building efficient transit systems, and trucking and erection capabilities Prefabrication process also allows for quicker adaptations in the interest of sustainability.

One other area that needs closer scrutiny is the consumption of potable water in concrete. With prolonged dry periods across many parts of the world, packed human densities around urban cities, water scarcity and drought have become the biggest concerns. Below poverty and middle class communities around the third world countries are the hardest hit with water scarcity. In this bigger context of water security concerns, it is very reasonable to find means and methods to reduce or even eliminate potable water consumption in concrete making. With several billions of cubic yards of concrete around the world every year; as of 2017, about 30 billion tons of concrete is produced annually on this planet (Monteiro et al., 2017). Because typical concrete mixes use about 40% of water as a percentage of cement and cement constitutes about a $7^{th}$ part of the amount of concrete, concrete production is consuming a devastatingly staggering 0.5 trillion gallons of water. This means the world has about 440 billion gallons less water every year because of concrete production. As per Boretti and Rosa (2019), the global annual water demand is at 4.6 trillion cubic meters as of 2021, which is equal to about 1200 trillion gallons of water. Approximately, 10% of this water is used for domestic human consumption; this is about 120 trillion gallons per year. All this means that the annual concrete consumption of potable water is cutting into half percent of domestic household water requirement all over the world. As such there is a very serious need for cutting down potable water based concrete production in the world to ensure a sustainable future for our next generations. Structural concrete mandates potable drinking water to be added in concrete, and this is followed worldwide. This requirement is driven by two materials, reinforcement steel and concrete itself. Reinforcement steel is highly susceptible to corrosion when it comes in contact with saline water. Chlorides and sulphates are highly deleterious to normal Portland cement concrete. However, if we adapt into using other novel material ingredients in concrete that can resist to chemical ingress and salinity, we will be saving a ton for humanity on this planet. In this area, fiber reinforced polymer reinforcement offers excellent opportunities. Unlike steel, polymers are made of composite materials that are very passive to chemicals in brackish or saline water. As such they do not need potable water requirement in the concrete mix. Pozzolanic materials in concrete such as fly-ash, slag, silica fume improves durability characteristics of concrete and improve its resistance to chemical ingress. A right combination of alternatives to steel reinforcement and Portland cement (O'Neill, 2023) will eventually deem potable water no more a requirement for concrete mixes. If we can achieve this, it will be the biggest contribution to sustainability goals of infrastructure development in the modern times.

**Maintenance Adaptation**

To achieve resilience to our infrastructure against natural disasters caused by extreme weather events triggered by climate change, it is not only important to adapt to engineering, design, construction and material adaptations but also to ensure long term health and robustness of the structures while they are in service or 75 to 100 years. Timely maintenance, repair, and rehabilitation (often referred to as MRR by maintenance operations teams) interventions are very essential in ensuring long term sustainability of infrastructure. In the days of increasing labor costs all over the world, it makes more sense to put timely resources on preventive maintenance in order to avoid expensive repairs at later stages.

In the current practice, preventive maintenance treatments are common for critical and public structures such as highways, bridges, airports, ports, and harbors; structures which typically serve large number of people. For instance, it is common for bridge agencies to perform preventive bridge inspections and maintenance treatments for bridge elements regularly. Federal Highway Administration mandates National Bridge Inspection standard procedures to be implemented by State Department of Transportation agencies for inspecting bridges once in every three years routinely and assign a condition rating for every bridge in each state. One of the purposes of these inspections is to identify preventive maintenance opportunities. The Bridge Inspector's Reference Manual (BIRM, 2022) comprehensively details the guidelines for inspectors about how to perform the inspections and rate the bridge condition. The bridge structures and asset management department then utilize the inputs provided by these inspectors to create a maintenance plan for the bridge along with prioritization of asset management resources for the bridge in the inventory of the bridges in the state. For this reason, bridges typically serve much longer than general buildings such as residences and offices (Vemuri & Jonnalagadda, 2023a).

However, the authors propose to start defining maintenance activities for residential and office buildings in order to achieve sustainable construction goals and build resilience into this section of infrastructure. Table 1 gives the guidelines for planning maintenance activities for buildings and offices. This planning is required to be performed before the construction of the structure commences. It is not to be left to the owner of the building to create such a plan or make it optional. The local approving authorities such as municipalities, and statutory code bodies should consider incorporating such maintenance plans and mandating their submissions and approvals at the onset of the construction of the facilities. Having such plans would save building owners and residents from catastrophic incidents such as residential condominium collapse in Surfside town in the outer suburbs of Miami, Florida in June of 2021 (Reinhard et al., 2021) due to lack of ownership and responsibility to the maintenance of the building and its component members. Table 1 does not include tall buildings and structures that are in high wind and seismic zones with heavy wind (Vemuri & Jonnalagadda 2023b, Vemuri & Jonnalagadda 2023c) and seismic lateral forces that need lot of location specific detailed analyses, so functional adaptation of existing buildings can be a real challenge.

**Table 1: Proposed Maintenance Activities For Sustainable Residential & Office Buildings**

| Type of Intervention | Type of activities | Frequency |
|---|---|---|
| Preventive maintenance | check wellbeing of structural members, check for corrosion, joints, spalling, plates, bolts, nuts, anchors, weld | 3 years for wood structures<br>5 years for concrete and steel structures |
| Special Maintenance | Specific maintenance to improve all the structural components | 10 years for all structures |
| Repairs | Replace plates, replace connections, remove spalling, grout fills, rust removal | Need based. Call is based on preventive maintenance inspection feedback |
| Rehabilitation | Member strengthening | Need based. |
| Retrofit | Member strengthening, Bracing, Additional connections, External tensioning (strands/bars) | Need based. |
| Reconstruction | Demolish and reconstruct | Only in the event of major interventions that do not justify repairs from financial and sustainability standpoint |

**Functional Adaptation**

Functional obsolescence is a major hindrance to sustainability of infrastructure. Once a structure has no function, it quickly becomes a point of discussion for demolition or reconstruction (Jonnalagadda, 2016). In the times of volatile economic markets and frequent instability in the world affairs, it is not uncommon for a structure to lose its functional relevance and become obsolete within as short duration as 15 to 25 years. These kinds of situations hit the sustainability goals negatively because demolition and reconstruction is a resource intensive process and sharply rises the life cycle costs of the structure. So it is essential that we minimize obsolescence as much as possible during majority of the design life of the structure (Jonnalagadda et al., 2015). While there are several causes of functional obsolescence as discussed in Jonnalagadda et al. (2015), its impacts on sustainability are very dominant and as such need to be planned and addressed well ahead in the life cycle of a structure.

Functional obsolescence is often driven by socio-economic changes that drive business needs and functional needs of a structure. For example, let us discuss a common scenario here. A building built twenty years ago with a design life span of fifty years in a promising residential zone would lose its property value because a chemical industry is constructed nearby, and a transit station is approved by government nearer to this residential zone. These developments will change the landscape of this area drastically making it poorly preferred for residential dwellings. So this existing residential zone loses its value and people eventually move out of the area. This place suddenly lost its function. Typically in these kinds of scenarios, it is common to demolish the residential buildings after a short life of 20 years and redevelop the entire estate land per the requirements of a new structural zone may be say an array of industrial warehouses. However, this is a bad decision for sustainability goals. The original residential building is only functional for 20 years whereas it is intended to have a life span of 50 years or even more. Demolition of these residential dwellings, redevelopment and reconstruction of warehouses will be a waste of resources.

For the above reasons, it is required to minimize functional obsolescence of the structure. However, it is not possible to control socio-economic conditions that trigger obsolescence. In view of this, in order to keep life cycle costs of the structure still under control due to function change, and in order to keep sustainability goals still reachable, it is essential to design and construct a structure that can adapt functionally. Functional adaptations to residential buildings are to be thought over at the design phase of the building. This includes full consideration to loads, design and detailing requirements of not only the existing structure but also to potential functionally adapted structure. What this means is that if the existing structure is a parking structure that is designed for a 50psf (2.4 kN/$m^2$) and it has decent probability to be functionally adapted into a shopping store in future with a live load of 75 psf (3.6 kN/$m^2$), due consideration is to be given for designing the parking structure for higher set of loads or frame the structure to be able to replace the current beam and deck members with higher capacity beam and deck members.

**Table 2: Framework for identifying functional adaptation needs for typical structures**

| Existing Structure | Existing Function | Potential Function (1st possibility) | Potential Function (2nd possibility) | Potential Function (3rd possibility) |
|---|---|---|---|---|
| Single storey building | Residential home | Small office building | Family store/cafe | Community school/centre |
| Single storey building | Small office building | Residential home | Family store/cafe | Community school/centre |
| Multi-storey building | Condominiums | Large offices | Hospital building | Shopping Centre |
| Auditorium | Function Hall | Event Hall | Theatre | Assembly |
| Parking structure | Parking Garage | Shopping store | Function Hall | Exhibit Hall |
| Manufacturing building | Material Fabrication | Gymnasium | Big Stores | Assembly area |
| Library | Education | Warehouse | Big Stores | Gymnasium |
| Warehouses | Godown | Manufacturing building | Library | Gymnasium |
| Technology/ Data Centres | Electronic Hardware | Hospitals | Storage Centres | Offices |
| Ball rooms | Dance halls | Gymnasium | Recreation rooms | Game points |

In Table 2, the authors provide some guidelines about identifying potential function changes over the design life span of the building and how to plan the building design early in its design phase in order to enable its successful adaptation to the changed function. It is possible that the predicted function changes can go wrong, and the building eventually may be required to be demolished and reconstructed. However, effort is to be made with full intentions to identify the potential infrastructure development plans in future at this location and propose plans for functional adaptation in the event such need arises during the early life of a structure. The guidelines provided by authors in Table 2 will provide a framework to identify functional adaptation needs of a building and means to accommodate for such changes without demolition of the building.

**Policy Adaptations**

Some of the most significant adaptations that are required to make our structures more resilient and sustainable are heavily dependent on our infrastructure development policies.

Policies set by local municipalities, building authorities, infrastructure development committees, elected officials and government departments need major adaptations in terms of regulating the implementation of the above types of adaptations into infrastructure development projects. In addition to that, government policies and vision play a vital role in enforcing key policies such as usage of sustainable materials and methods in infrastructure development, cut carbon footprint of construction, and promote construction of energy self-sufficient structures. However, while the above adaptations are mostly to be carried out by engineers, designers, construction contractors and owners of the structures, policy adaptation is driven by elected officials and political houses. The interests of our echo systems, our environment and the future of our generations are to be given priority over short term issues and interests.

The authors recommend the following policy adaptations to be considered for mandatory regulations by elected officials and both houses in order for our engineers, designers, and contractors to be able to carry forward with the other adaptations we discussed in the previous sections.

- Mandate building energy self-sufficiency and net zero policy plans and requirements prior to building plan and construction approval
- Revise and increase the ratio of green areas to constructed areas in the community.
- Discourage construction of large sized houses by reducing incentives or increasing taxation
- Mandate growing trees that contribute to high oxygen levels and are native to the area.
- Remove landscaping requirements for the sake of beautification, instead place value on the ecological contribution of plants and trees.
- Provide incentives for reduced home sizes, place higher energy costs on bigger houses using a slab system.
- Clean energies such as solar and wind are to be incentivized for the generation of energy to the building.
- Composting and recycling requirements are to be strictly mandated and enforced on communities prior to trash disposal.

## Conclusions

In this paper, which is the second part of the overall study, the authors propose the additional set of adaptations that we need to make to our current construction and maintenance methods. The need to improve the efficiency of our methods and the ways to embrace new methods and materials with the bigger objective of cutting the carbon footprint of our construction and incorporating resilience into our structures against climate change induced extreme weather events is put forward. In addition to this, the authors also propose the various functional adaptations of some common structures and provide framework to identify the potential functional changes of the building in future and create proactive functional adaptation plans to be created during the building plan approval process and make it mandatory as part of application submission process. The authors provide a list of common buildings with preferred choice of functional adaptations they can quickly be modified into.

However, the framework for that in terms of layout, engineering and design are to be determined during the building approval phase in order to ensure smooth functional transition of the structures in the event of their obsolescence early in its life span. An engineering judgement is required in deciding if it makes economic and sustainable sense in implementing the functional adaptation of the building. A quick way to determine this is to look at what phase in the life of the structure is this functional obsolescence hitting and how does it impact the life cycle cost of the structure and its energy and carbon footprint in comparison with demolition of this structure and rebuilding new one. The design life span of the building, the life cycle cost of the materials, labor and maintenance, the relative impacts on carbon footprint, energy and resources together will determine the decision towards functional adaptation of existing building or demolition and new construction.

Separate research on evaluating the impacts of functional adaptation of a building and comparing it with the impacts demolition and new construction will provide valuable insights on what timeline in the life span of a structure does it make sense to adapt to the new function of a structure. Other factors such as size and scale requirements of the new building play important role but they are completely external to this context because functional adaptation of the existing building is possible only when the size and scale of the transformed building is similar in layout to the existing building.

Last but the most important adaptation that is required is the policy adaptation. Big scale changes and paradigm shift in engineering happens only when it is backed by policy adaptations. Our structural planning, building and construction procedures are very much created several decades ago possibly going back to 50 to 75 years and there are no major modifications hence forth. Most of the code updates, revisions that happen to ACI, ASCE, IS, BS and EN codes and the committees that work on these revisions are driven by consensus. As such these revisions are often limited to very minor obvious errors. They take several decades to put forward any major framework changes. This is understandable because major changes will offer more resistance and lose traction quickly. However, it is time to incorporate major changes to the way we have been taking infrastructure decisions. Environmental sustainability of our infrastructure building has never been a serious factor in the engineering, design, construction, or approval process of structures; however serious policy changes can drive the changes. The authors believe that environment, carbon footprint, energy efficiency, resource waste, habitat protection, minimalistic intervention and simple living should be given the highest priorities in the building approval, engineering, construction, maintenance and adaptation or demolition process. This is an extremely difficult task and not attractive because it needs us to put our self-interest in the back seat and collective interest of human race in the front seat. However, this alone can decide the future of our next generations, our planet and if humans can continue to survive on this planet in healthy and happy ways.

## Disclaimer

The opinions and views expressed in this paper are purely of those of the authors' and do not in any way represent the views or opinions of the affiliate organizations or institutes.

## Contributions

The second and third authors contributed to the impacts of global warming on climate change and extreme weather events. The adaptation needs of our infrastructure and the proposed solutions were contributed by the first author.

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