A SUSTAINABLE TRANSITION TO INDUSTRIALIZED HOUSING CONSTRUCTION IN DEVELOPING ECONOMIES
Foreword

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The following analysis and case study examples suggest our perspective on how industrialized construction can make a meaningful difference for future global housing. At the same time, we recognize that the topic of housing is not an easy subject. A conversation about housing also is a conversation about equity and politics, about economics and urban planning, and about architecture and technical implementations. Housing construction spans the tension of local cultures and global supply chains. The full environmental, societal, and political implications of introducing industrialization into developing economies are not yet clear.

Nonetheless, this report is meant to engage in the conversation about meeting the global demand for housing within the material and environmental limits of our planet. To this end, we think industrialized construction has an important future role.

Richard Boyd
Senior Engineer
Arup

The urban populations are predicted to grow by 2.4 billion by 2050, a 64% increase. The new construction demanded by this growth will be significant – some estimates suggest the total global floor area doubling in the same period. At the same time, the built environment must largely decarbonise. Resolving the tension between these two megatrends is the defining challenge of this generation of built environment professionals.

Most global construction practice is typified by reliance on low-skilled manual labour and limited use of technology, creating buildings which perform poorly in terms of safety, resilience, comfort and environmental impact. These challenges are particularly acute in low- and lower middle-income countries, where most of the growth mentioned above will take place.

The rapid upscaling of capacity to meet demand requires the construction industries in these regions to radically transform themselves. This transformation, already underway but maturing in the next decade, gives a once-in-a-century opportunity to avoid the missteps and challenges of construction in higher income countries, by consciously choosing an alternative development path.

The concept of industrialized construction has the potential to be the model for that alternative development path. It describes an approach whereby safety is improved (both in use and during construction), resilience is increased, skills are enhanced, waste is reduced and environmental impacts are mitigated, while also providing rapid growth in capacity to meet demand.

* https://www.weforum.org/projects/future-of-construction

Global cities are rapidly urbanizing. The demand for urban housing is greater than ever before. Approximately 200,000 people already relocate to urban centers each day*. By 2030, an estimated 60% of humanity will live in urban areas. As urban population increases, so will the need for housing. By the end of the century, we will need about 2 billion new homes. In particular, developing economies will feel the greatest impact of urban growth.

In the next decade, emerging markets can anticipate a construction growth rate estimated at 65%*. At the same time, construction of urban housing and its associated infrastructure will significantly deplete global resources unless we can rethink our current processes and materials. The construction industry is the largest global consumer of material resources. In developed economies, the construction industry is notoriously poor at resource management. For example, in the United States, 50 million tons of new and virgin construction materials – the equivalent of roughly 50 Boeing 747 jumbo jets - are discarded into landfills. These are wasted materials from the process of construction, waste that is not even part of an actual building.

We have to do better. Without rethinking existing methods and systems of construction, the building of future urban cities in developing markets will accelerate our world past acceptable thresholds of resource usage.

As described in the following report, we see industrialized construction (IC) as one potential alternative to design, manufacture, and assemble structures more efficiently.

Yet there is little work in the literature examining current implementation of industrialized construction in rapidly urbanizing geographies, nor on the comparative environmental impact of industrialized versus conventional construction in these locations.

This paper therefore makes a timely and valuable contribution to one of the most important and pressing topics for discussion when considering the future of the global built environment. By examining current implementation, assessing environmental impact and analysing factors influencing future adoption, it lays the groundwork for private sector development plans for the construction section in Addis Ababa, Cape Town and Nairobi, three of the most important markets for built environment growth in the next 30 years. I recommend it to policymakers and designers, investors and construction clients, manufacturers and contractors operating in these cities and in the wider region, and look forward to participating in conversation it will inevitably inspire.

* https://www.weforum.org/projects/future-of-construction
EXECUTIVE SUMMARY

A SUSTAINABLE TRANSITION TO INDUSTRIALIZED HOUSING CONSTRUCTION IN DEVELOPING ECONOMIES

This publication is a result of a one year research project in collaboration between Arup through the annual Global Research Challenge (2018) and Chair of Innovative and Industrial Construction of ETH Zürich.
As the world becomes increasingly urbanized, global cities must provide adequate and affordable housing for growing populations. The regions with the fastest rates of growth are in developing economies, where cities tend to have limited access to the resources required — namely the capital, materials, and skilled labor — to meet the rising residential demand. This coincides with increasing pressure to minimize the environmental impact of the built environment globally. To limit climate change to 1.5°C, cities need to significantly reduce emissions. Material consumption and energy usage for buildings and infrastructure require reductions of 33% by 2030 and 50% by 2050. To achieve this, substantial interventions must be made such as improving material efficiency, enhancing building utilization, switching to low carbon materials, adopting low-carbon cement, and reusing building components.1

Providing housing for growing and urbanizing populations while minimizing its environmental impact is likely to be one of the greatest challenges facing the built environment in the 21st century. This challenge is especially difficult for developing economies, where a predicted 65% of growth in the construction industry is expected to occur due to the rapid increase of urban population.

An emergent trend in the building sector called Industrialized Construction (IC) could help alleviate these future challenges facing the global housing industry. IC is an umbrella term referring to broad strategies applying principles of industrialization and manufacturing to improve the productivity and predictability of construction projects. IC approaches in the residential sector often are characterized by changes to conventional business models, use of advanced technologies, and continual improvement of standardized processes. In addition, IC can yield additional capacity of design and construction activities that is not easy or possible to do with current construction methods. The capacity comes in forms of the use of digital tools that allow for design optimization and construction techniques that facilitate products to be manufactured and fabricated more efficiently.
Moreover, IC draws in and supports emerging sustainable construction materials and products that require industrialized manufacturing ecosystems. Strategies used in IC such as off-site construction, standardized assembly, and product platforms have the potential to increase the quality of products, increase material efficiency, and lower the cost and time required for projects to be completed.

There is great potential therefore for IC to reduce the environmental impacts while providing additional capacity for global housing. Nevertheless, the overall life cycle performance depends on a wide variety of contextual factors. These, combined with the complex network of influences affecting the housing and building market, demonstrate that proper planning and forethought required to ensure that any potential transition to IC can achieve the intended outcomes.

This report aims to explore the micro- and macro-influences of Industrialized Construction applications in the specific context of developing economies. Data is drawn from field visits to three cities—Addis Ababa, Nairobi, and Cape Town—in sub-Saharan Africa. The report begins with a micro-level view of building elements. A life cycle analysis is conducted to compare the environmental impacts of different construction materials and methods. The life cycle assessment approach evaluates both the product stage (raw material supply, transport, and manufacturing) and construction process stage (transport and construction installation process) of residential building projects in the case study cities. This report categorized wall and slab building elements across three construction methods: conventional, partially industrialized, and fully industrialized. Case-specific key environmental hotspots are identified and analyzed across the construction elements.

The results indicate that shifting from conventional to industrialized construction methods could reduce the overall impact of housing construction from production through construction. Impacts across product and construction process stages are reduced by a third from conventional to fully IC. Much of the improvements is seen on the product stage where a shift in type of materials, reduction of construction waste, and efficient design strategies are implemented. Evaluation of the type and quantity of materials used in element construction shows various impacts, introduces emerging lightweight and sustainable materials such as cross-laminated timber and identifies design strategies to reduce material consumption such as moving from solid to hollow-core slab designs. The partially industrialized construction elements, however, typically have a higher impact than conventional methods, and should be improved before being applied at scale.

Next, a macro-level view focuses on the intricate ecosystem influencing IC adoption in the three case cities. Using a systems analysis approach, nineteen impact factors are identified that influence IC adoption in the sample cities. The factors can be broadly categorized, and range in scale from micro-factors such as product performance to macro-factors such as the local society’s perception of IC. An impact matrix is created that evaluates the relationship between decisive impact factors. Based on this impact matrix, characteristics of system factors - Active, Passive, Ambivalent, and Buffering - are identified and plotted on a system grid. The condition of infrastructure in a city is found to be the most active impact factor for the adoption of IC. The report gathers and analyzes the current state of the impact factors to understand potential future development of IC in these cities.

The results of both analyses present a range of potential outcomes — negative and positive — for the overall adoption and performance of IC strategies and products. Using existing practices and emerging insights around IC methods and innovations, the report offers a roadmap to demonstrate a range of possible scenarios for IC adoption. Each pathway includes examples of objectives and specific levers for local decision-makers to transition to IC in a responsible and intentional manner. The tool is especially intended for urban areas in developing economies, expanding on how policymakers, city leaders, local entrepreneurs, and existing industry practitioners might consider adapting IC to unique contexts in order to achieve ambitious goals around housing construction and a sustainable built environment.
PROBLEM AND BACKGROUND

A Global Housing Crisis

Access to adequate shelter has long been recognized as a fundamental human right that is critical to achieving a minimum quality of life. Despite this, today, more than one billion people live in substandard housing. The failure to minimize that gap has been termed “the global housing crisis.”1 If two current global development trends continue, the challenge to properly house the global population will only increase.

TREND #1 - THE GLOBAL POPULATION IS INCREASING

Today’s population of 7.7 billion people according to the medium-variant projection is estimated to grow by more than 2 billion people by 2050.2 A significant portion of this growth will occur in developing countries (see Figure 1). The population will double in many of the world’s least developed countries over the same time span. Over half of global population growth is predicted to be in sub-Saharan Africa alone.3

TREND #2 - THE GLOBAL POPULATION IS URBANIZING.

Compared to rural areas, cities offer better access to economic opportunities and important social services such as high-quality education and healthcare. More than half of the people in the world already live in metropolitan regions. This percentage is likely to grow to 68% by 2050.3 However, urban growth is not projected to evenly spread. Almost 90% of the expected population growth in cities will occur in Africa and Asia.4 This will be led by both rural migration to cities and population growth within them. For example, Ethiopia’s capital city of Addis Ababa is expected to triple its population between 2000 and 2030 and the population of Nairobi, Kenya is projected to increase from roughly 4.5 million to over 14 million in the next 30 years.5 Major cities in India and China are projected to grow by as much as five times during the same period.6 In developing countries especially, the physical centralization of cities allows local governments to efficiently fund and install the infrastructure necessary to deliver basic needs like electricity, potable water, and waste management services. Better access to these amenities typically results in a higher potential quality of life in cities, further accelerating rapid urban growth.7

THE NEED FOR AFFORDABLE, QUALITY HOUSING

Dramatic rise in urban populations introduces high housing demand in these regions. This demand can stress local services and can limit a local government’s ability to meet the growing needs of its residents. Furthermore, the urbanization of cities in developing economies is occurring at a historically unprecedented rate compared to that of developed economies.8 This only increases the common issues of urban development such as traffic congestion, air pollution, high living costs, homelessness, and informal or slum developments. Though the above challenges are influenced by a variety of factors, one critical component to any proposed solution is a sufficient supply of quality local housing. Increased housing supply can directly improve affordability across a range of incomes — although housing supply for low-income residents is typically only met through government intervention.9 Available and affordable housing unlocks many of the social benefits and employment opportunities afforded to urban residents. In addition, better housing quality improves the health and safety of inhabitants by providing proper indoor air quality and insulation. The ability of a city to meet the above needs is an important signal of its overall resilience. In fact, the City Resilience Index developed by Arup points to safe and affordable housing as the first provision of a city’s health and well-being.

Figure 1: Map of population growth rates around the globe from 2020-2025

Slum developments — informal communities that lack access to one or more basic necessities — are clear signals of a large and unmet demand for affordable housing in a city. Globally, the absolute number of urban residents in slums is rising even though the proportion is slowly decreasing. The UN Habitat estimates that approximately one out of every eight people in the world lived in slum conditions in 2016.10 Inadequate and expensive housing creates clear and pressing challenges for public health and equity.
A Global Environmental Crisis in the Built Environment

The global housing crisis is not the only challenge facing the building sector. The built environment must also respond to the global climate crisis. The planetary boundaries (PB) — a concept proposed by a group of international scientists — define the safe operating space for humanity to ensure a functioning and stable Earth system (which characterizes roughly the last 10,000 years of global conditions).

However, since the Industrial Revolution, humans have had significant impact on their Earthly surroundings — meaning the planet’s stability could be gravely compromised.11 Broad studies on climate change by the Intergovernmental Panel on Climate Change (IPCC) further verify the importance of achieving low emissions profiles: they predict that global net anthropogenic carbon dioxide emissions should be net zero by 2050 to limit global warming to 1.5 °Celsius and not have long-lasting or irreversible impacts.12 Illustrated in Figure 2, the nine biophysical process boundaries show the thresholds under which humanity should still be able to thrive and develop, as well as current performance levels based on the metrics indicated (though two are without measurable control variables).13

Nearly all of the nine boundaries are influenced either directly or indirectly by the construction and operation of our living infrastructure. Based on the large proportion of global emissions and resource usage attributable to the built environment, a massive shift from traditional approaches to the building industry is required to meaningfully address the already-worrisome environmental metrics displayed here. Particularly in developing economies where rapidly growing urban areas will take up 65% of the next decade’s growth in construction,14 it is critical to minimize the short-, medium-, and long-term impact of this construction on the planetary boundaries which are already in crisis.

Overall, the construction and operation of the built environment contributes to approximately 39% of all greenhouse gas emissions.15 As a result, the Intergovernmental Panel on Climate Change (IPCC) has called for critical improvements to the construction and operation of the built environment to tackle the pressing environmental crisis.

SUSTAINABLE CITIES

There are various reasons that the rise in urbanization is also a positive trend towards sustainability. This is largely because one fundamental urban development strategy is to promote higher population density. Concentrated population growth can encourage and support efficient public infrastructure spending (on electric grids, water supply, waste management, and public transportation, among other things) as well as generally improve economic dynamism and social integration for the urban population. Compared to sprawled development, dense growth has a higher potential to decrease automobile dependency often associated with severe congestion and air pollution.16

Emerging research shows that even these more abstract impacts can also meaningfully improve a city’s and community’s overall resilience.20,28,29 Infrastructure and population density also makes it easier to plan and implement comprehensive climate resistance measures to mitigate the negative impacts of global warming at the city-scale — a consideration of rising importance for many climate-vulnerable cities.30 The end result is a clear correlation that makes densification an important urbanization strategy to minimize the environmental impact and improve the resilience of metropolitan regions even as their populations grow.31

EMBODIED CARBON OF BUILT ENVIRONMENT*1

Embodied Carbon refers to the carbon emissions associated with materials and construction processes throughout a lifecycle of a building or infrastructure.

UPFRONT CARBON OF BUILDINGS

Upfront carbon encompasses emissions associated with materials production and construction processes. The construction industry is the largest consumer of raw materials and other resources. The built environment consumes roughly 50% of global steel production and more than 3 billion tonnes of raw materials.32

The construction process itself requires abundant and inexpensive natural resources that can be sourced, refined, assembled, and disposed in a linear economy model (i.e. take-make-dispose). Potential recycling solutions exist in construction, but none have yet succeeded at a meaningful scale. Estimates place construction waste as being responsible for 15-30% of all urban waste. It is particularly alarming that in traditional craft construction methods, it is estimate that between 1-10% of purchased (i.e. virgin) materials directly leave the site as waste generated in the building process. The global production of these resources impacts significant global warming impacts. The production of cement and steel alone accounts for nearly 10% of global carbon dioxide emissions.33

Concrete can also negatively impact local air quality due to the release of cement kiln dust, which introduces pollution-related health risks to residents near production facilities.34

Ultimately, 11% of all global carbon emissions come from embodied carbon, a proportion which will only rise as energy efficiency reduces the impact of the operational phase.35 Use of materials that are non-toxic and sustainable is a crucial component of green building.36 Rethinking how buildings are designed, used, maintained, and treated at end-of-life is a topic of great interest to researchers and practitioners alike. As building resources become more scarce and disposal of waste becomes more expensive and (or/and strictly regulated), it is increasingly important to transition from the conventional linear economy practices in construction.

OPERATIONAL CARBON OF BUILDINGS

Another significant environmental impact in buildings comes from energy used during the operational phase. Energy use in buildings accounts for 28% energy related carbon emissions. This not only reflects the energy (e.g. electricity, natural gas, kerosene) consumed by users but also the energy and resources needed to repair buildings over their useful lifetime. Water consumption is increasingly vital in reducing climate change impacts as well,37 especially in severely water-scarce regions like South Africa. Climate change imparts further stress on these operational demands, exaggerating the external conditions which the built environment must be designed to mitigate and endure. For example, the higher frequency and severity of extreme weather events like heat waves dramatically increases the cooling capacity required for a building to maintain livable conditions year-round. These factors indicate an urgent need for well-planned and holistically resilient infrastructure that reduces environmental impact throughout its life cycle.
An industry productivity crisis

The construction industry also finds itself in a productivity crisis. Over the past 25 years, productivity metrics in construction have stagnated. The industry productivity improvement is far outpaced by the productivity improvement of other industries such as manufacturing. Scholars and industry leaders have searched for explanations and solutions to productivity stagnation. Fragmentation that occurs from project to project results in the “prototype” mentality, where each building is conceived, designed, and constructed anew. Technical knowledge and experience is not often transferred across projects but is embedded within individual professionals. Evidence of this is in the fact that overall, the construction industry generates and utilizes less data than other industries.32

The project delivery models of construction are further plagued by fragmentation between stakeholders partially due to misaligned incentives and adversarial contract mechanisms that lead many projects to lengthy (and expensive) litigation after completion. Poor integration between specialized trades like mechanical, electrical, or plumbing can further complicate project dynamics and obfuscate responsibilities for collaborative tasks.33

These structural characteristics of the industry - along with others - have contributed to inefficient material usage characterized by a high degree of physical waste on projects.34

In the context of developing economies, additional and more severe challenges for the construction industry include a lack of access to skilled craft labor35 and knowledge workers. In this case, knowledge workers could even just refer to familiarity with tools like computer and information technology. For example, across all middle and low income countries, only 23% of the population are internet users (compared to nearly 70% in high income countries).36

Low availability of locally- and affordably-produced materials can further limit the building industry in developing economies. Low access to local capital is another common trait that often leads to high foreign investment into construction projects in developing economies. This can either promote or inhibit local industry capacity and workforce development.33

To summarize, the existing methods and means of housing construction can be problematic, especially in developing economies. The lack of productivity improvement in the industry has led to pointed calls from industry and researchers of an industry that must “Modernize or die”38 and could be ripe for industry disruption from new technologies39 and business models.40

Figure 3: Globally productivity trends and compound annual growth rate of industries, adapted from McKinsey’s report.

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THE PROMISE OF INDUSTRIALIZED HOUSING CONSTRUCTION

To improve productivity, entrepreneurs and innovators in the construction sector have been rethinking design and engineering processes, infusing digital technology and automation, improving supply chain management, and restructing contractual frameworks to align incentives between stakeholders. Industrialized Construction (IC) is an emerging approach that is well-suited to achieve this transformation, particularly in the housing sector. Many principles of IC have been derived from the automotive manufacturing industry. When these principles are combined, they result in a fundamentally different approach to construction and development than traditional practice.

What is Industrialized Construction?

In this report, “Industrialized Construction” is used as an umbrella term inclusive of concepts such as prefabrication, preassembly, modular, offsite, and robotic construction. In general, IC is used to describe a business model and technical orientation that links design and fabrication using an integrated building process and organizational structure. While IC has many different forms, it can be helpful to understand IC using the holistic framework presented here. This framework presents the more prominent aspects of IC; however, future business models and strategies might offer even more divergent opportunities to achieve IC goals in innovative ways.

SIMPLIFYING DESIGN FOR MANUFACTURE IN THE UK

The primary mission of WikiHouse is to lower the knowledge barrier “to design, manufacture, and assemble beautiful, low-cost, low-carbon buildings into the hands of every citizen, community and business.” They intend to provide an intuitive web-based software tool that can combine standardized parts to ensure the design can be manufactured locally with flexible, on-demand “micro-factories.” This means that the WikiHouse platform enables high quality structures with great design and geographic flexibility for both production and assembly, an ideology summarized as “share global, manufacture local.” The two major requirements are a reliable source of plywood and a CNC (numerical control) machine to shape the construction elements. Currently, their supply chains are limited to the United Kingdom, the Netherlands, and New Zealand, but they are still expanding their capabilities and reach with the help of major partners and collaborators such as Arup.
Blokable is a real estate development startup founded in 2014 in Seattle, Washington. Blokable has since expanded along the West Coast of the USA. Blokable has implemented a vertical platform that integrates design, planning, permitting, off-site manufacturing, delivery, on-site construction, and ongoing operational support into one transparent and easily-managed service. The Blokable Building System allows standardized manufacturing while creating endless site variation. Combining physical standardization with a vertically-integrated business model, Blokable drastically reduces the cost and time of developing real estate, delivers a high quality product that reduces long-term operating and maintenance costs, and maximizes equity creation.

Blokable produces modules in a factory that can be stacked up to 5 stories high on foundation or over a podium. Blokable’s pre-installed monitoring system, BlokSense, assists in real-time tracking of safety, usage and performance data enabling optimization of energy systems, air quality management, critical building functions, and proactive repair and maintenance. These provide the advantage of substantial savings in maintenance and operations costs while improving the quality of life for residents.

Founded by real estate and technology industry veterans, Blokable is a self-performing developer that builds market rate projects for its own portfolio and also provides design-build services to nonprofits as a fee developer. Blokable’s nonprofit structure expands prosperity and equity in communities by building high-quality, low-cost, connected housing at scale at below-market cost.

Regardless of the specific strategy adopted, several potential benefits have been identified when IC concepts and methods are integrated into the house-building process. The main advantages are:

- **Improved safety:** The labor conditions in factory settings are improved thanks to optimized work flows that minimize risk to workers. Factory employees complete tasks within close proximity to the ground and the work can be designed so as to reduce repetitive muscle strain and fatigue.
- **Weather independence:** The impact of adverse weather on working conditions and productivity is reduced because elements are typically produced off-site within indoor factories or workspaces.

**Levels and Advantages of Industrialized Construction**

Implementation of IC can occur to differing degrees. The simplest approach is typically the production of prefabricated or standardized individual components of a building such as a roof or wall system. A more complex approach is factory-based production of entire volumetric units to complete the majority of construction activities off-site.

IC strategies like these frequently take place in a factory setting. But innovative methods such as 3D printing — an example of which is highlighted here — could take place on-site and transform the phases of construction in novel ways. IC can also be integrated with conventional construction techniques, like with machine-aided masonry installations. Applications like these are considered partial (hybrid) IC construction. Partially IC offers unique advantages and challenges of its own. For the purpose of this report, the diagram gives an overview of the characteristics conventional, partial, and full industrialization of construction.

Some recent software-focused entries into the IC space aim to provide digital platforms to design and manufacture full building systems by simplifying assembly. One such company, Wikihouse, is featured here.

**Community-Aided Designs with 3D-Printed Homes**

Founded in 2014 and headquartered in San Francisco, USA, the nonprofit New Story gained popularity as one of the first industrialized construction companies to adopt 3D printing technology for at-scale housing development. After building thousands of homes across Latin America using more traditional methods, New Story is now developing a 3D-printing approach in collaboration with technology partner Icon.

The latest printer, called the Vulcan II, can print an entire concrete home in less than a day. Most of the construction process is automated using the device which helps lower the cost substantially compared to traditional methods. The team highly prioritizes the operation of the machine by locals in order to develop new technical skills and stimulate the local economy. The first set of projects will be built in a yet-undisclosed location where the community’s current shelters are low-quality shacks that flood and fall apart during the long and intense rainy season. This causes families with little means to rebuild nearly every year. For the new development, locals were directly involved in the design process to develop the handful of possible layouts for each new home. New Story also implements a survey software to be used by the homes’ occupants so that their input can inform future developments. The project to be completed this year will be the world’s first community entirely built using a 3D printer.

Quality improvement: The strong emphasis on the pre-planning phase reduces the possibility of spontaneous on-site changes. Factory production also enables further precision to enable closer alignment between design specifications and the final as-built conditions.

Shorter execution time: The use of more standard design elements, multiple production lines, and automation (full or partial) reduces on-site construction time.

Higher cost predictability: IC can enable more consistent and reliable cost estimates. This is further improved by shared insights across projects being embedded into robust IC processes and platforms.
Can Industrialized Housing Construction meet housing demands while reducing environmental impact?

Industrialized Construction has the potential to reduce environmental impact through advances in digital tools, manufacturing technology, and supply chain integration.

In general, the potential for Industrialized Construction to reduce environmental impacts can be summarized into six categories. The six categories highlight impact factors influencing the performance and potential of IC for environmental impact reduction. Inherently, IC is heavy on leveraging digital tools that allow efficient design, better communication with stakeholders, standardization, and data driven decision-making. IC also integrates concepts from manufacturing that reduce construction waste and achieve quality through factory-controlled environment. Nevertheless, the categories also point out factors such as operational energy performance of IC products that is not necessarily intrinsic to IC but are crucial for the overall sustainability of the products. See a highlight on Blokable, which focuses on collecting performance data during the use phase to improve efficiency in the design of their affordable units.

However, until now, there has been limited data and case studies that explore how IC might help solve emerging challenges such as the global housing crisis, the global environmental crisis, and the industry productivity challenges. Can a shift from traditional to Industrialized Construction help meet global housing demands while limiting the environmental impact of future housing projects? Furthermore, if so, how can the construction industry undertake such a sustainable transition, especially in developing economies? These two questions are the driving point of this report.
INDUSTRIALIZED HOUSING CONSTRUCTION IN SUB-SAHARIAN AFRICA: A COMPARATIVE CASE STUDY

Three detailed case studies are used to assess the potential and requirements of IC for housing in developing economies. We use a multi-level analysis approach that looks at the product-level, company-level, and city-level.

Two main tasks guide the analysis:
1. Conducting an environmental impact assessment of currently available construction systems and systems that involve IC.
2. Analyzing the ecosystem for adopting IC at scale in the focus cities.

In addition to extensive literature review, the analysis is anchored by field trips to the case study cities for interviews with local construction companies and other experts in the building sector. Task one was conducted using a Life Cycle Assessment on building elements. Task two was conducted using a Formative Scenario Analysis. Further information on the full methodology used can be found in the appendix of the report. The combination of these two approaches is intended to generate knowledge about the impact of housing delivery methods and begin a conversation about a sustainable transition towards Industrialized Construction practices specifically in emerging economies.

The focus of the analysis for this section are three case study cities in Africa: Addis Ababa in Ethiopia, Nairobi in Kenya, and Cape Town in South Africa. The study is focused here because of the region’s high proportion of global urban population growth, and on the basis that they were similar enough to warrant comparison but different enough to lend unique contextual insights.

**ADDIS ABABA, ETHIOPIA**
Addis Ababa’s local government launched the Integrated Housing and Infrastructure Development Program in 2004 with aims to produce large amounts of affordable housing as well as accelerate gainful employment opportunities for local residents. A major strategy of this policy has been to facilitate micro and small business enterprises (MSE), particularly for companies seeking to build more low-cost housing.

**NAIROBI, KENYA**
Nairobi’s households are dominated by renters, with approximately 86.4% of the city’s residents living in rented dwellings. Partially as a result of this dynamic, the National Housing Policy for Kenya has prioritized poverty of its residents as the main obstacle to affordable housing in the region rather than targeting the housing deficit specifically. Most housing-oriented programs are driven instead by the local government and — similar to Addis Ababa — are strongly motivated by the need for gainful employment.

**CAPE TOWN, SOUTH AFRICA**
Cape Town, as compared to the other two case study cities, is more established and slow-growing in terms of its population and its economy. To counter-act this stagnancy and address historical spatial and social inequality, the local government released a Municipal Spatial Development Framework focusing on dense, transit-oriented growth. Due to this and the city’s extreme water scarcity event in 2018, investments in efficient and resilient infrastructure have increased emphasis moving forward.
As shown in Table 1, the case study cities have similar populations but differ considerably in their densities and access to basic amenities. The high growth rates, coupled with the large percentage of the urban population living in slums, are signals of the high housing demand in each city. Some of the unique contextual aspects are highlighted below, accompanied by vignettes for two IC companies already operating in Addis Ababa and Nairobi:

Table 1: Various characteristics of the three case study cities

<table>
<thead>
<tr>
<th></th>
<th>Addis Ababa, Ethiopia</th>
<th>Cape Town, South Africa</th>
<th>Nairobi, Kenya</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population (2019)°2</td>
<td>5,295,000</td>
<td>4,524,000</td>
<td>4,556,000</td>
</tr>
<tr>
<td>Population growth rate (2019 approx.)°3</td>
<td>3.8%</td>
<td>2.49%</td>
<td>3.88%</td>
</tr>
<tr>
<td>Population density (people per km²)°4</td>
<td>5,164</td>
<td>1,530</td>
<td>4,850</td>
</tr>
<tr>
<td>Urban population in slums°6</td>
<td>74%</td>
<td>23%</td>
<td>56%</td>
</tr>
<tr>
<td>Urban population with access to electricity°8</td>
<td>96.6%</td>
<td>93.5%</td>
<td>81.1%</td>
</tr>
<tr>
<td>Urban population with access to basic sanitation°9</td>
<td>18%</td>
<td>35%</td>
<td>76%</td>
</tr>
<tr>
<td>Tallest completed building (meters)°10</td>
<td>118</td>
<td>139</td>
<td>200</td>
</tr>
<tr>
<td>Buildings over 100 meters (completed)°11</td>
<td>2</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Primary Industry°12</td>
<td>Agriculture, services</td>
<td>Services, trade, transport</td>
<td>Agriculture</td>
</tr>
<tr>
<td>Primary Electricity Source°13</td>
<td>Hydropower</td>
<td>Coal</td>
<td>Geothermal and other renewables</td>
</tr>
</tbody>
</table>

AB-HAM Enterprise plc, founded in 1998 in Addis Ababa in Ethiopia, offers an advanced steel framing system that allows clients high building performance while maximizing customization. Having operated longer than most industrialized construction firms, they rely on a well-established network of suppliers and customers around the world. Though all of their manufacturing capabilities are local, they import materials and more advanced products such as the Decra roofing system from New Zealand and the Dakeï acoustic ceiling from Japan among other technologies. These globally-sourced elements include sophisticated roofing systems, heating and cooling solutions, plumbing, and even manufactured furniture. These are all combined to complete the cost-effective and material-efficient product delivered by AB-HAM. After construction, AB-HAM provides a 50-year warranty on buildings to cover any faults in the building system. (Image credits: AB-HAM Smart Steel Presentation)

UNIFYING A GLOBAL SUPPLY CHAIN NETWORK IN ADDIS ABABA

Based in Nairobi and established in 2014, the real estate company KOTO Housing Kenya uses element-based industrialized construction techniques to make high-quality structures more affordable. As a licensee of a Malaysian company, KOTO uses their parent company’s technology, a panel composed of Expanded Polystyrene (EPS), that is lightweight and enables cost savings in labor and structure delivery. Because their system of panels can be configured in many layouts, they have a high degree of flexibility. This allows KOTO to offer multiple predetermined floor plans to gain the benefits of standardization while highlighting designs that optimize for quality of life features like energy efficiency and comfort. KOTO Housing focuses on projects across the country, targeting three key building areas: housing, education, and health. This is part of their broad mission to make critical infrastructure more adaptive and responsive to market demand while providing high-quality local employment opportunities in the process. (Image credits: KOTO Housing)
Products and their environmental performances

Although studies find that IC has potential to reduce environmental impacts, this does not mean that better environmental performance is guaranteed in every application. The following section analyzes a variety of specific construction methods to determine when IC strategies are more or less environmentally impactful in comparison to conventional practice.

LIFE CYCLE ASSESSMENT

A bottom-up approach is used to assess the environmental performance of products. In particular, the analysis includes inputs and processes during Product stage (A1 Raw material supply, A2 Transport, and A3 Manufacturing) and Construction process stage (A4 Transport and A5 Construction installation process) of the lifecycle stages of a building as defined in EN 15978. The indicator used to assess the products’ environmental impact is Global Warming Potential (GWP), which is a measure of how much atmospheric heat is trapped by greenhouse gases emitted relative to carbon dioxide.

The LCA is conducted on two of the primary structural system components: slabs (including columns as structural supports) and walls. The building elements selected for detailed analysis were grouped into three categories by the construction methods used to produce them: conventional, partial IC (hybrid of conventional and IC methods), or fully IC as described in the promise of Industrialized Housing Construction section. In this analysis, the building elements have different functional equivalents. The comparison is done using the common unit of reference of one square meter area. Detailed description of the methodology can be found in the appendix of this report.
CONSTRUCTION METHODS IN:

ADDIS ABABA, ETHIOPIA

In Addis Ababa, conventional internal and external walls are predominantly constructed with concrete masonry. The concrete masonry consists of hollow concrete blocks (HCB). A cement and sand mix mortar is used between the HCBs and for plastering. The introduction of the gypsum wall, a fully-industrialized wall system is a shift from the conventional concrete masonry system found in Addis Ababa. Gypsum wall systems are primarily manufactured off-site and assembled on site. Other conventional wall systems in Addis Ababa include a solid concrete wall and other fully-IC wall systems include light Gauge Steel (see appendix for full details).

Overall, the conventional wall systems in Addis Ababa have higher GWP as compared to fully-IC applications. One key explanation is the difference between the type of materials used: the absence of concrete and lightweight materials used in the fully-IC wall example reduce its overall environmental impact considerably.

The conventional solid slab dominates the Addis Ababa market. The solid slab is made of reinforcement steel and concrete and requires scaffolding and formwork for on-site casting. The ribbed slab system is emerging as an alternative for mid-high rise building projects for its speed and achieving larger span. Ribbed slab systems introduce HCBs between girders and beams to reduce material use. The construction requires less scaffolding and formwork when compared to the solid slab.

In contrast to the wall systems, the conventionally built slab systems used in Addis Ababa have lower GWP compared to the partial IC (ribbed) slab. The main difference occurs because the ribbed slab uses more materials. Although the hollow sections of the HCB are intended to reduce the amount of concrete used – thus reducing cost - the ribbed slab is much thicker and uses more steel reinforcement, which results in increased GWP impact.

Gypsum Wall Factory, Addis Ababa
NAIROBI, KENYA

Conventional wall systems in Nairobi are built using stone masonry. Stone masonry are similar to the concrete wall in Addis Ababa, but instead of using HCB’s a limestone is used. An emerging partial IC solution is prefabricated expanded polystyrene (EPS) with an on-site application of concrete. In addition, prefabricated light gauge steel construction systems offer a fully-industrialized solution. These systems are made with steel profiles for structural performance and a thin steel-sheet on the exterior for cladding.

Within conventional wall systems in Nairobi, the stone masonry wall has the lowest GWP. The primary reasons for this include the absence of concrete and the use of locally available materials. In the partial IC category, the EPS system has higher product as well as construction process stage Impacts. The fully IC application – light gauge steel (LGS) – has less GWP compared to most available wall systems.

The solid slab is the predominate slab system in Nairobi. Similar to the ribbed slab system found in Addis Ababa, the hollow pot slab system is emerging as an alternative.

The hollow pot slab is suitable for larger spanned slabs without introducing columns. As was the case in Addis Ababa, the partial IC slab system used in Nairobi has a higher GWP as well. Once again, the production stage is responsible for the majority of the larger relative impact.

The expanded polystyrene (EPS) factory in Nairobi is shown in the image.
In Cape Town, the conventional wall system is brick masonry. Brick masonry walls are built the same way as the other masonry walls, but instead of HCBs or limestone, sand-lime bricks are used. An expanded polystyrene (EPS) solution is emerging in Cape Town. This is similar to Nairobi, with the note that EPS elements found in Cape Town replace steel reinforcement with an internal magnesium board and external fiberglass mesh. In addition, a cross-laminated timber (CLT) wall system represents a fully IC that is prefabricated off-site. CLT is made by joining layers of wood at a perpendicular angles to achieve structural rigidity.

In comparing the systems, conventional wall systems in Cape Town have higher GWP than industrialized alternatives. The partial IC system of EPS— similar to the EPS system in Nairobi — uses hybrid materials and methods, but the use of concrete makes the system perform similarly to conventional construction wall systems. From the fully IC category, cross-laminated timber (CLT) shows the best performance across all methods analyzed. CLT impacts are significantly reduced at the production stage, where other methods require energy-intensive machinery and processes to prepare the materials. This is a major advantage for local company, XLAM, featured below.

The conventional slab system in Cape Town is the solid slab. In addition, hollow core slab systems have existed within the Cape Town construction market for some time. Hollow core slab systems are prefabricated off-site. In the case of Cape Town, the performance of fully IC methods shows a significant reduction in GWP compared to the conventional solid slab. This can be explained by the design strategies implemented: the hollow core has reduced thickness compared to the conventionally-built solid slab. Furthermore, the use of structural voids reduces the amount of material required.
From analysis of the various wall and slab systems, the diagram below provides a generalized trend regarding the environmental performance of products as the level of industrialization increases. The sections that follow highlight the detailed differences in the relative environmental impact of each phase within the production and construction process. The conclusion of this section also includes a visual to show the quantitative trend across the three methods analyzed.

**KEY ENVIRONMENTAL HOTSPOTS**

- **Type of material:** Across the three case studies, there is a shift in the types of materials used from conventional to partial to fully IC. Lighter materials such as LGS and CLT are used predominantly within IC applications. Across the construction methods studied, the use of cement and reinforcement steel are seen to substantially increase the ultimate impact. Potential future applications of fully IC such as 3D printed concrete walls were studied. The cement-intensive concrete mixture used in 3D printed wall systems could incur added environmental impact. Compared to a conventional concrete mix with 206 kg of cement per meter cube, a 3D concrete could require up to 765 kg of cement in the concrete mixture.62 Hence, if an alternative material is used – such as a “noncrete” mixture with little to no cement - the advantages for environmental sustainability could significantly increase.

- **Primary material saving:** Once materials are specified, design strategies can help reduce the amount of materials used. Fully IC systems can take advantage of repeated design and product platforms to avoid overdesign of the system. Some of the case projects indicated an increase in material requirements due to a lack of confidence in conventional construction processes. The controlled environment provided in a factory setting of IC on the other hand increases confidence in designers and engineers that the products will be fabricated and assembled correctly.

- **Transportation for raw material production:** It is important to note the distance materials travel to reach production site. Across the three construction methods, there is a shift in the types of materials used and where they are sourced as illustrated in figure 12. Conventional built elements tend use locally produced materials such as cement. Partial IC tends to balance the proportion of materials imported or sourced within-country. In the case of Fully IC, construction materials tend to be imported due to their novelty to the manufacturing industry for the case study cities. However, this is not always the case – e.g. CLT production in Cape Town.

- **Factory processes and energy mix:** The environmental impact from producing individual elements is higher as the level of IC usage increases. This stems from the factory processes involved with IC.

The results have shown that the impact of this phase can vary greatly between the methods in the case study cities. The reason here is that factories use electricity from the local grids - which have very different emissions intensities across the cases - while construction site activities (e.g. equipment and generators) are powered by diesel fuel.

This change in the local impacts of factory produced products. For example, the electricity emission of facilities in Addis Ababa has lower impacts because electricity is generated primarily by hydropower.65 If a fully IC LGS system is constructed in all three cities, the fossil-fuel heavy electricity mix of Cape Town will show a 7.87 GWP in Kg CO2-eq/m2 from the electricity use within the product stage. This number is 30% higher than that reported for Addis Ababa and 50% higher than Nairobi.

**PRODUCT STAGE (A1-A3)**

Type and amount of material has large influence

Hybrid products have higher environmental impact

Efficient design and production strategies realized

Production impacts depend on grid electricity sources

Buildings could have low lifecycle impact

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**Conventional**

In-country: Imported

Material production

**Partial IC**

In-country: Imported

Material production

Element Production

**Fully IC**

In-country: Imported

Element production

---

Figure 12: Raw material sourcing
CONSTRUCTION PROCESS STAGE (A4-A5)

Transportation to site: The materials for many of the conventional construction methods studied were bulky and heavy materials which significantly increased the environmental impact during this phase. In the case of IC, finished products are transported. Fully IC methods have the advantage here due to their use of lightweight materials like CLT and LGS as well as the fact that they transport less materials overall.

Construction/Assembly of elements: Conventional construction has more on-site activities, giving it the highest environmental impacts followed by partial IC and fully IC. However, it can be said that impacts during this phase are negligible across all three methods when compared to other stages.

Figure 13 displays the average product and construction process stage impacts of wall and slab systems studied. The results indicate that shifting from conventional to industrialized construction methods could reduce the overall impact of housing construction from production through construction.

Impacts across product and construction process stages are reduced by a third from conventional to IC. Much of the improvements is seen on the product stage where a shift in type of materials, reduction of construction waste, and efficient design strategies are implemented. The partially industrialized construction elements, however, typically have a higher impact than conventional methods, and should be improved before being applied at scale. This was best illustrated by the poor environmental performance of partial IC solutions such as the ribbed slab in comparison to conventional solid slab systems.

It is also important to note that each data points shown above are merely the average performance of the systems found in this research. While some patterns emerge, this is a generalized trend and should be applied on projects with caution. Individual local assessments with more detailed specifications should be carried out before definitive environmental impacts of these wall and slab systems can be quantified for a specific given site location.

USE AND END-OF-LIFE STAGE

Due to the complexity and lack of sufficient data, the use and end-of-life phases are not explicitly studied in this report. It is important to note that the performance of building elements in the production and construction stage does not represent their true life cycle performance. Although the intensive planning and design optimization potential of sophisticated IC methods could substantially reduce environmental impact during these later phases as well, quantitative analysis of this hypothesis could not be performed at this time.

Additionally, the role of building typologies — what is built and where — is a critically important component in the environmental performance of any building system, and could greatly influence the ultimate impact of a given product, project, or building method.

With that said, the results of this analysis find that environmental impacts from the product stage far outweigh the impacts of the construction process stage. Fully IC systems trend toward lighter, less-impactful products, thus the opportunity is to use IC to develop better products with only a minimal tradeoff of GWP impact at the construction process stage.

CIRCULAR AFFORDABLE URBAN HOUSING IN NAIROBI

Orkidstudio aims to deliver design solutions that are founded on human-centered principles and priorities environmental performance, functionality, and local resources. Orkidstudio aims to look at the building industry holistically and articulate a pragmatic vision for the future of construction in East Africa. Their mission is to develop a viable new typology for affordable urban housing in Kenya, looking to new and improved locally produced building products, prefabricated assemblies, and inclusive development models while adhering to the principles of circularity.

Circularity: Collaborating with suppliers and academia to improve the circularity and embodied energy of the construction industry in a long-term development. Researching usable parts of current local waste streams and making them available to the community.

Affordability: Using prefabrication to reduce cost, developing smarter designs, creating long term skills and manufacturing hubs, collaborating with future inhabitants and contractors (formal/informal) with the aim to lower construction cost and to stimulate livelihood.

Affordability: Using prefabrication to reduce cost, developing smarter designs, creating long term skills and manufacturing hubs, collaborating with future inhabitants and contractors (formal/informal) with the aim to lower construction cost and to stimulate livelihood.
Understanding the adoption of industrialized housing construction

If IC can offer a better environmental solution, what can cities do to increase the adoption of Industrialized Housing Construction as a more sustainable alternative for housing in developing economies? Understanding the environmental benefits is not enough. City leaders, policy makers, and local entrepreneurs need to understand and address the barriers that might exist in the complex industry ecosystem: the network of internal and external factors that influence IC adoption.

Analysis of the three case study cities reveal some factors that are likely shared across any global city and other factors might be unique to a particular city. The following section highlights nineteen individual factors identified in the analysis of the three cities. In addition, the interdependencies between the individual factors are identified using systems analysis to identify and understand the influences to IC adoption. In other words, this section answers how IC adoption and development might increase according to existing conditions in the local context.

SYSTEMS ANALYSIS: IMPACT FACTORS

The following factors were determined via an extensive literature review on barriers and facilitators of IC adoption in nine countries as well as interviews with experts from the three case study cities. The core of the analysis was to identify and assess major impact factors to provide insight into a specific topic in a specific context. Identifying decisive impact factors serves as a basis to construct potential scenario developments of a case in a Formative Scenario Analysis methodology.66

In this case, the focus was to understand current states of industrialized housing construction in these three cities and present an aggregate, qualitative set of significant influences on its development (more scope and detailed steps can be found in the appendix). Ultimately, six broad categories and nineteen individual impact factors were identified and explained below. The list is not exhaustive but nonetheless calls out the most prominent influences revealed through the analysis.

- **Product performance**
  covers the performance of IC products
- **State of industry**
  covers the state of the construction industry
- **State of city**
  covers issues related to infrastructure planning and delivery
- **State of market/economy**
  covers state of workforce and financial status of a city
- **Policies and regulations**
  state of a cities’ commitment towards IC
- **Society**
  state of end customers perception towards IC

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Planned Construction Project, Cape Town
PRODUCT PERFORMANCE

QUALITY OF PRODUCTS
The quality of the finished products and the improved performance potential during the use and maintenance phases of the building. The quality improvement of IC products compared to conventionally built ones is measured in this impact factor.

TIME OF CONSTRUCTION
The time required to deliver a housing unit. How does IC perform in the planning, production, and installation of products on-site compared to conventional methods.

DESIGN FLEXIBILITY
The degree of design flexibility a client has with IC methods. Historically, this was a shortcoming of IC products that adopt mass standardization to achieve other performance outcomes (like time or cost savings) to the detriment of flexibility. As evidenced in some of the company vignettes, however, this traditional paradigm is shifting with new IC approaches.

MATERIAL EFFICIENCY
The amount of material savings achieved by IC methods through design strategies and/or assembly method. This might include actual building materials like concrete or wood, or temporary supporting materials and resources such as formwork.

PRODUCT COST
This impact factor covers the product cost performance of IC compared with conventionally constructed building products.

STATE OF CITY

TRENDS OF DENSIFICATION
This is the pattern of dense population of an urban area and typically signaled by mid to high-rise residential buildings to accommodate such development. IC is well-matched with constructing such developments. This is associated with the speed of assembling elements instead of constructing them on-site. Hoisting materials and elements with IC techniques is found to be more efficient than traditional construction.

CONDITION OF INFRASTRUCTURE
The current state of infrastructure, including road quality and the supply of potable water and reliable electricity. These elements are crucial for most IC applications that rely on off-site, power-dependent facilities and sufficient road conditions to transport large prefabricated elements. A lack of high-quality infrastructure can thus erode IC’s maximum potential benefit.

MANUFACTURING CAPABILITY
The physical or chemical transformation of materials of components into new products, often through machines in factory facilities. The factor evaluates the availability of this capability, both in scale and transformation potential. Higher capacity and sophistication in the manufacturing sector can benefit IC.

SAFETY
The safety of workers throughout the construction process. Using industrialized construction methods typically improves health and safety conditions and reduces the number of accidents in the building sector.

STATE OF MARKET AND ECONOMY

UNEMPLOYMENT RATE
The amount of people who do not have but are seeking work, often measured as the percent of the total labor force. In all three case study cities, the labor productivity improvements often offered by IC methods was seen as a negative if local unemployment was high. The perception was that IC could replace or reduce local employment opportunities. The actual labor impact of IC is unclear, however, and potentially a net positive to job growth (as with the introduction of many new technologies). Alternatively, in more developed countries, the need for less on-site construction workers is often viewed as a benefit.

INVESTMENT
An indicator of the overall local capital available. This includes investment into the purchasing of plants, machinery, and equipment, as well as land improvements for the construction of roads, railways, schools, offices, hospitals, private residential dwellings, and commercial and industrial buildings. Investment can be from government or private sources, foreign and domestic.

INITIAL COSTS TO SET UP AN IC COMPANY
Initial cost of establishing an IC company, including potential expenditures for a factory, machinery, employee training, and an ICT platform among other costs. The novelty of IC methods in many countries can also increase perception of risk from early investors.

SKILLED KNOWLEDGE WORKERS SUPPLY
The number of workers who have technical and/or professional skills required to work in and with complex systems and technology. This focuses especially on the education and skill level of the local labor force, and can be as familiarity with operating computers and conducting internet-based communication and software.

POLICIES AND REGULATION

AVAILABILITY OF BUILDING CODES FOR IC
This refers to the accessibility and specificity of local building codes for IC. As constructing housing using IC methods is relatively new, more available codes could directly inform and benefit the standardization of IC elements and methods. That could further advantage IC by simplifying and streamlining the approval of IC designs that are consistent across projects.

INCENTIVES FROM GOVERNMENT FOR IC
The commitment of government agencies to promote the use of IC methods. The focus lies especially on the amount of incentives given to encourage the use of prefabrication and automation and ease the process of adopting them. It also includes the investment in research and development of new concepts that could optimize the construction process. Incentives can range from tax levies to requiring IC methods on government-built projects.

SOCIETY

PERCEPTION OF IC BY END CONSUMER
Users have the final say regarding the success of any business model and IC companies are no exception. Bad experiences in the past often lead to a bad perception of IC as a whole, while successful (and well-publicized) projects can transform public opinion and be a powerful motivator of expansive IC ventures.
IMPACT ASSESSMENT AND ANALYSIS

Once the above impact factors were identified, through an impact matrix, they were rated using a five-point measurement scale to identify their likely causalities in relation to each other (a detailed table of this impact factor matrix can be found in the appendix). Figure 14 provides a visual representation of these relationships.
Though the full ecosystem is important to show, the network is obviously complex and required simplification in order to hone in on specific insights. To do so, the impact factors were plotted on two axes — Figure 15 here — based on the raw number of other factors they influenced or were influenced by based on the matrix. This system grid of impact factors reveals four main sections that are created by two red dotted lines in the graph. The dotted lines represent the mean values of “activity” (having direct influence on other factors) on the y-axis, and “passivity” (being directly influenced by other factors) on the x-axis. This results in four high level categories:

**ACTIVE IMPACT FACTORS**

In the top left section are impact factors that have high impact on the system. In other words, changes in these factors directly impact a large number of other factors. Indicators in this category are: condition of infrastructure, time of construction (for IC products), design flexibility, demand of housing, manufacturing capability, and quality of IC products.

**PASSIVE IMPACT FACTORS**

In the bottom right are factors that are frequently influenced by other factors, but do not directly influence other factors themselves (relatively). Initial costs to set up an IC company and perception of IC by end users are both categorized in this section.

**AMBIVALENT IMPACT FACTORS**

These factors have strong two-way influence. Product cost, incentives from the government for IC, and the market share of IC are in this region. Although very important, ambivalent impact factors are also categorized as having dynamic, unpredictable effects on the system.

**BUFFERING IMPACT FACTORS**

These are factors that have below average activity and passivity values and are believed to have low to moderate influence on the overall system. The availability of skilled craft workers supply, skilled knowledge worker supply, material efficiency, availability of building codes for IC, safety, and investment are in this category.
ANALYSIS OF FEEDBACK LOOPS

While useful to highlight the biggest and most direct influences, honing in on specific feedback loops can lend more tangible insights as to the unique system dynamics of IC adoption. In particular, three interesting feedback loops within the complex ecosystem of impact factors are identified below, with plus (+) or minus (-) signs denoting the influence of one factor on another. In some cases, the relationship is not direct, as visualized, but one or more steps in between are not visualized for the sake of emphasizing broader takeaways. Each description will follow one cycle of the loop to elaborate on the proposed interactions.

There are two important details to note while analyzing these smaller feedback loops:

1. The relationships shown are emblematic of the current state of the proposed ecosystem. Some feedback loops may trend towards an equilibrium state that diminishes or eliminates the influence of these relationships or changes the dynamics altogether.

2. The loops are artificially isolated: external factors may cause one factor to decrease even as another factor positively influences it. For instance, in the first loop, increasing the market share of IC will not automatically decrease the demand of housing. By making housing construction faster and more affordable, however, a high proportion of IC in the market should encourage and enable housing supply to more closely match demand than if traditional construction methods still dominate the industry. This relationship remains true even if housing demand continues to rise due to external factors.

FEEDBACK LOOP 1

This simple but important feedback loop between market share of IC and demand of housing shows the indirect relationship between the two impact factors. An increase in the market share of IC should decrease the demand of housing by enabling greater and rapidly deployable housing supply. Inversely, high demand for housing increases the need for faster and more cost-effective construction, providing strong market incentives that favor novel IC methods.

FEEDBACK LOOP 2

A reinforcing feedback loop between four impact factors. Increased flexibility in design leads to an improved perception of IC from residents, increasing demand for IC and gradually improving its market share. An increased market share of IC will also require and employ more skilled knowledge workers across the industry. Then, improved market competition and internal expertise can lead to more sophisticated design options (i.e. flexibility) within the IC framework.

FEEDBACK LOOP 3

If a growing city has high unmet housing demand, more investment will be required to meet rising needs of infrastructure and services as well. Investment is also likely to be attracted because high housing demand is often a sign of growing local economic and employment opportunities. An increase in investment towards infrastructure (including industrial facilities and reliable utility provision) should indirectly increase a city’s manufacturing capabilities. This has a positive influence on the IC market by increasing the potential scale and sophistication of IC methods, making IC practices more feasible and its benefits more pronounced. That includes improving the potential speed and affordability of housing constructed via IC, allowing housing supply to keep better pace with demand.
Lessons learned: recommendations for policy, business, and engineering leaders

Across three case studies and the scope of the analysis, one insight is clear: local context is important. Though this report identifies general trends as IC adoption rises, the status and trends of certain factors in any given city are dependent on local contextual factors. Such local factors have critical impacts on which interventions might be most effective in driving positive change.

Moreover, technical advances in IC will likely emerge in tandem with new ecosystems and business models within the construction industry. These changes should be leveraged to cope with the evolving industry environment.

The following pages highlight key lessons that are worth emphasizing for local decision-makers.

IC PRODUCT PERFORMANCE IN CASE STUDY CITIES

The market share of IC in all three cities is recorded to be below 10%. IC in these locations is implemented primarily at the individual element level and not at a building system scale. The perception of IC by end users was reported as low. Despite some activity in the IC space (see the three sample companies highlighted in earlier vignettes), all three cases are in the very early phases of IC adoption. That being said, the few applications already seen there are mixed but promising:

QUALITY OF PRODUCTS AND TIME OF CONSTRUCTION

Each of the case study cities reported significant potential advantages for IC products in these two categories.

PRODUCT COST

Nairobi and Cape Town report that IC products currently cost more than traditional construction methods, though experts in Addis Ababa reported modest cost savings.

DESIGN FLEXIBILITY

Experts in all three cities view IC products as having measurably less design flexibility compared to conventional construction products.

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--- Slightly worse | -- Worse | --- Much worse
+ Slightly better  | ++ Better | +++ Much better

Figure 16: Case-specific IC product performance

IC PRODUCT PERFORMANCE - ENVIRONMENTAL POTENTIALS

- Quality improvement in IC from conventional construction contributes to lower environmental impacts.
- Reduction of flexibility and higher prices could lead to lower uptake of IC products hence environmental benefits not being fully utilized.
UNEMPLOYMENT RATE AND INDUSTRIALIZED CONSTRUCTION

Based on the above factors alone, Cape Town seems to be well-suited to transition towards fully IC methods. However, a critical limitation to IC’s expansion is due to the city’s extremely high unemployment rate. In 2018, South Africa had the second-highest unemployment rate in the world. Experts from all three cities report that this is very discouraging to IC and other initiatives that increase the productivity of the construction process. The perceived influence is that the “innovative” methods are actually removing valuable jobs from the labor market, leaving existing workers stranded and worsening unemployment.

This is in contrast to many developed nations such as the USA and UK, where skilled craft labor is extremely limited and indeed been a major motivator for the adoption of IC approaches.

As an example, the company Modroof (highlighted below) designed their process to remove the need for skilled labor almost entirely. Their strategy to gain local approval is to design a modular roof panels system that local residents can help install on their own.

CONDITION OF INFRASTRUCTURE AND MANUFACTURING CAPABILITIES

Between the three cities, the combination of water supply, electricity and road provision is highest in Cape Town. This lowers the costs of producing and transporting IC building elements locally, favoring IC approaches that favor off-site work and pre-assembly of components. Addis Ababa, on the other hand — the city with the lowest relative infrastructure conditions — may be less amenable to such practices due to bigger challenges in procuring the resources to power and operate an off-site manufacturing facility.

Partially as a result of the infrastructure conditions, Addis Ababa and Nairobi have similarly limited manufacturing capabilities (as measured by the value added by the manufacturing sector in 2018, shown below). This is not unique to these cities: per capita output of the manufacturing sector in Sub-Saharan Africa is estimated to be 30% lower than other developing regions. Interestingly, in the same time span, China’s manufacturing output has expanded dramatically both in technical sophistication and capacity. This has led to increasingly affordable imported products from China that challenge the business of local suppliers.

Part of manufacturing capacity is the human capital of cities. The quality and knowledge of the local labor force is a key driver for industrialization and manufacturing in many countries.

In the case study cities — especially Addis Ababa and Nairobi — the low supply of knowledge workers presents an obstacle to the manufacturing sector expansion. With that limitation, advanced IC methods (with high level of element pre-assembly) could be more difficult to adopt and operate at scale while remaining cost- and time-competitive with conventional construction. This suggests alternative pathways will be required to reduce the environmental impact of construction in these contexts.

MANUFACTURING CAPABILITIES - ENVIRONMENTAL POTENTIALS

- Higher manufacturing capabilities reduce transportation distance of materials and elements.
- Industrialized construction can better assimilate in places where higher manufacturing capacities are found.
- Clean source of electricity is essential to harness the benefits of manufacturing
- The availability of skilled craft/knowledge workers increases the quality of products.

The emerging understanding is that a transition to IC methods can actually offer more jobs, available to a more diverse workforce than those currently offered in the construction market. However, in the context of rapidly developing economies, understanding impacts and perceptions of IC on the labor market will be a critical task for IC entrepreneurs and innovators and should not be underestimated.

As an example, the company Modroof (highlighted below) designed their process to remove the need for skilled labor almost entirely. Their strategy to gain local approval is to design a modular roof panels system that local residents can help install on their own.
Based out of India, Modroof uses local waste materials to manufacture a durable, affordable, and environmentally-friendly roof option. The company, founded by recent engineering graduate Hasit Ganatra in 2014, focuses on the enormous demand for quality alternative materials for roof construction in slum developments. "In numerous cases… people manage to get the walls together and up but roofing turns out to be the bottleneck," observed Hasit. Existing roof options include tin and concrete, but these tend to be poorly insulated, noisy during rainstorms, and expensive to install and maintain. Modroof, on the other hand, developed a custom process to use recycled cardboard and agricultural waste to produce lightweight, waterproof, and fire-resistant modular panels that ease installation and replacement. The team also partnered with local microfinancing businesses to offer feasible loan repayment plans for their customers. In the next generation of their product, Modroof plans to include modest solar power capabilities and expand internationally to reach the market of 1 billion slum dwellers worldwide.

Though industrialized construction can offer a solution, its use without proper local considerations can deliver less optimal results. One example of such an outcome was in Mexico in the early 2000s. As part of a government-funded program, hundreds of massive, single-story housing developments were built across the country using generic, "identikit" building systems called "small, concrete cubes." The $100 billion spent on the program was marred by poor planning and corruption, leaving many of the developments without running water or functioning sewage. Partially due to the execution by large construction companies without sufficient guidelines or regulations, the communities include very little outdoor space or architectural character. The developments, described as having "an indifference to human needs", represent the potential of industrialized construction pursued for purely utilitarian means and without proper alignment with the needs of communities. It illustrates the need for proper forethought in the design and execution of building programs in order to complete broad, ambitious goals. (Image credit: Wired)
GLOBAL OUTLOOK FOR IC

Based on the case studies and lessons learned from IC applications in other countries, an even broader set of influences should be considered in emerging cities in general. Factors like geography, government structure, public trust, and political stability were not significant impacts in the case study cities, but could all significantly influence IC adoption elsewhere. Therefore, local expertise is required to assess and adapt the appropriate solutions for any city.

The general trends of IC adoption visualized here, however, are intended to be applicable to any urban area. Regardless of the goals in question, the remaining sections can inform the decisions of relevant stakeholders from industry professionals to city planners and other government officials.

It is important to recognize that cities’ urbanization strategies as well as their priorities in achieving the stated goals are important and varied. This can provide non-obvious or indirect opportunities and challenges to particular IC methods. For example, a zoning strategy that encourages high-rise buildings might inherently benefit volumetric modular approaches. This is because they can use repetitive features between modules and across floors to optimize the process and maximize advantages. Alternatively, a city that insists on an ad hoc, on-site inspection process can minimize the advantage of an IC platform. Therefore, the interactions between local government policies and IC need to be comprehensively analyzed to reveal the points of conflict or synergy with IC potential. The following sections expand the knowledge gathered from the case study analysis to create a global outlook for IC.
Road Map to IC in Developing Economies

PATHWAYS TO IC ADOPTION

As referenced throughout the report, “Industrialized Construction” encompasses a wide range of potential construction strategies without a presumed best option for an individual project or for industry practice at large. And indeed, too much IC without proper consideration for the local context can be nearly as damaging as no IC implementation at all. That being said, if adopted thoughtfully and responsibly, IC applications can address many of the most pressing issues in the housing construction industry. This requires well-designed interventions that encourage the best aspects of IC while attempting to avoid its worst outcomes. Though this is a subjective and moving slider of impacts, a simplified set of possible implementation levels is explained and diagrammed here.

The scenarios shown in Figure 20 are by no means all-inclusive or mutually exclusive, nor are the interventions listed as precursors to those scenarios. In presenting them, this report merely intends to show that Industrialized Construction can be used to the benefit or detriment of its surrounding context. Overall, there is potential for IC to be an integral component of any urban area’s sustainable development strategy, but this should be done with local context and local objectives in mind.

BUSINESS AS USUAL/COLD IC

The basic scenario for a city is one in which no public or private entity takes the initiative to drive IC adoption. The construction and housing market continue to operate with economic and material inefficiencies, fail to meet the high housing demand of the rapidly growing city, and likely have major difficulties adapting to more environmentally sustainable practices.

LUKEWARM IC

A possible strategy for a city grappling with high unemployment, this pathway offers a subset of IC’s potential advantages while prioritizing the preservation of skilled labor jobs. Though the wide range of benefits ultimately achievable by IC might not be fully realized, it would still improve upon many of the shortcomings of conventional methods. This could be an optimal pathway for stakeholders without the ability to make the transformative changes suggestive of more ambitious IC initiatives, whether due to a lack of technical skills or available capital.

COZY IC

Portrayed as a generic “optimal” adoption level, this scenario includes both high housing production and quality, flexible design options. This scenario would require a stronger knowledge sector than the lukewarm pathway, but does not necessarily result in a decrease in available employment opportunities. Instead, IC at this level could utilize software tools to expand the capacity and abilities of the housing construction industry. Such implementation would also require stronger collaboration between multiple disciplines and stakeholders, public and private alike (though this can be done via business integrations as well).

BURNING IC

This pathway describes IC taken to the extreme but devoid of any socially-oriented procurement strategy. Though it is likely to provide sufficient housing supply quickly and cheaply, it could also result in characterless and unpopular housing units. With past examples like in Sweden’s Million Homes program or the projects in Mexico highlighted in the report. This level of IC adoption is bad for consumers, bad for the industry, and bad for the city. Strategies and interventions discussed above are intended to help avoid this outcome.
PRODUCT AIDS, LEVERS AND ACTIONS FOR IC

In addition to the various benefits described above, figure 21 shows a generalized relationship between high level city goals and characteristics, specific IC product aims, and the different levers and actions that might serve the desired outcomes of IC and the construction industry at large.

CONTEXT:
As mentioned before, every city has a unique blend of goals, priorities, and available resources. Thus, the context column can and should include important city-wide factors and conditions that would influence IC adoption. In addition to examples provided in the impact factor analysis in the previous section, some important influences could be the degree of corruption or stability in the local and national government, specific natural hazards such as seismic or flood risks, or even geographic boundaries (e.g. mountains or coastlines) that constrain urban growth and land use. This is where local experts need to consider the unique characteristics of their city to ensure the more granular product aims of IC methods can be achieved without conflict.

PRODUCT AIDS:
For there to be any transition to IC, its product performance must be competitive in at least some aspects such as cost, speed, and/or quality. Design flexibility is variable but must allow for a sufficient degree of variation to accommodate unique customer needs. Material and energy efficiency (especially during production and construction) is especially important if environmental goals are a high priority, though it also partially contributes to potential cost savings.

- **Speed:** In the context of providing housing in a rapidly urbanizing world speed is a big issue. Faster delivery of housing has been a key reason for IC products to be chosen as an alternative. This trend is expected to grow as the rate of urbanization grows.
- **Cost competitive:** Though IC could potentially result in measurable cost savings, products only need to be cost-competitive with traditional products to drive adoption. If used for affordable housing, cost reduction should be a higher priority.
- **Design flexibility:** Some minimum flexibility is required to avoid over-standardization, but this category tends to be a moving target. Progress could be made through product configurators and advanced digitalization techniques.
- **Material/Energy efficiency:** For sustainable construction practices, this is a critical aim for minimizing short- and mid-term impacts of the built environment. It is important to pair this with sensible material choices to minimize the adverse influences from transportation and energy used during production.
- **Quality:** As the case studies show, the reputation IC has for higher quality products is a strong motivator for its implementation in many contexts. This is an important aim for reducing lifecycle costs (both financial and environmental) as well as improving the lived-in experience of our built environment.

![Figure 21: How IC products and aims can align with broader city goals and decisions](image-url)
LEVERS AND ACTIONS:

Lever represent control points that could be used to encourage sustainable IC development. Actions are specific decisions that could be used to exercise the levers in order to shape and encourage IC adoption in a positive way.

To achieve the product aims while aligning with broader city goals, a handful of major levers are presented in the diagram above and are elaborated below to demonstrate the domains of intervention. These decision points are primarily for local government, whose cooperation is important to ensure any industry-wide change is aligned with short- and long-term city goals.

- **Building codes:** more consistent and transparent processes for the submission, evaluation, and approval of building permits and plans is helpful to the entire building industry. It can streamline the planning phase of projects, reducing the total time for new construction while ensuring the urban growth strategies are followed across all new development. For IC projects, specifically, more reliability in the early phases of a project can critically align with the need to maintain consistent production and delivery flows in off-site facility operation. Additionally, building codes should continually be updated to include sustainable and innovative materials and products.

- **Manufacturing capabilities:** this lever can lead to achieving most of the product aims. Increasing local manufacturing abilities will add value to local construction materials. This in turn creates a regional value-chain that can potentially grow the construction industry. The construction industry is an important job market in developing economies especially in the labor-intensive trades of conventional construction. The increase in manufacturing capabilities through automation should also address and integrate craft production.

- **Skilled craft/knowledge:** especially in developing economies, training the labor force in basic skills like computer and internet competency, word processing software, and spreadsheet management could be extremely beneficial for a wide range of industry sectors. This would provide a critical foundation for advanced IC applications due to their dependence on up-to-date information and communication across the full material supply chain and with multiple project stakeholders. Investing in skilled craft/knowledge will also support the harnessing of computational design and production. Programs to train more skilled craft/knowledge labor would also benefit the entire building industry.

- **Government incentives:** without explicitly stated regulations around the building industry, informal and ad hoc solutions are inadvertently favored. Introducing even basic standards around important issues like safety on the construction site or material waste disposal can improve the quality of the built environment as a whole without being too restrictive. They could then be embedded directly into the platforms and processes of IC companies which ensures compliance across projects. There should also be policies and regulations to facilitate sustainable IC products into the market.

- **Sustainable infrastructure planning:** as mentioned in the introductory section, promoting higher density is an effective strategy to optimize the spending and performance of critical infrastructure and services while also reducing per capita emissions. Though this isn’t automatic, public transportation, electric grids, potable water provision, waste disposal, education, and medical care could all significantly benefit from policies encouraging density. Even if this promotion leads to mid-rise buildings and not the towering skyscrapers seen in New York City or Tokyo, IC products can benefit from the repetitive processes inherent to multi-floor developments. That would help them achieve the economies of scale that tend to fulfill product aims regarding cost and speed.

- **Condition of infrastructure:** availability of quality urban infrastructure of water, electricity, and roads is vital not only for IC but for the entire building industry. Powering and improving the electricity grid with reliable renewable sources is a challenging but important task for any city to reduce its overall emissions. In the case of IC, progress in this goal is important to further improve its environmental performance, especially during the production phase. Additionally, for IC products to fulfill the product aims of faster and more cost-effective construction, reliable grid performance is crucial to maintain predictable off-site facility operations.
Demands on our built environment are high and rising. On the macro-scale, this includes a global climate crisis that puts immense stress on the resources and materials used to construct buildings as well as the energy required to maintain and operate them. Simultaneously, growing populations concentrating in metropolitan regions give rise to extremely high housing demand in these areas, requiring large amounts of new housing construction.

On the micro-scale, research and experience continue to reveal the strong influence our physical surroundings have on our psyche and quality of life. As such, we expect and deserve more intentionality around building design and construction that optimize for features like thermal comfort, air quality, daylight, and usability, among others. Lastly, underlying all of these challenges are enormous inequalities across the globe and within cities that further emphasize the importance of sustainable urban development.

One emerging strategy to address these issues is IC. Like any technology or innovation, IC is not inherently good or bad, just as past experiences show. But within the broad range of approaches available via IC methods and their evolution, there is huge potential to improve on the diverse set of critical challenges in urban environments.

The application of sustainable IC is studied and presented in this report to highlight the adoption and adaption of IC methods in developing economies.

The general takeaway points are:

PRODUCT-LEVEL
Products need to be carefully designed considering local materials and supply chain. Products also need to be constructed efficiently.

COMPANY-LEVEL
Internal capacity and knowledge in the construction sector need to be nurtured and expanded. Sustainable products need to be further developed.

CITY-LEVEL
A vision for a sustainable built environment should be created. This can also guide the early adopters of innovative materials and methods. Additionally, housing developers and builders tend to lack the desire to go beyond regulatory or statutory requirements. We suggest that a sustainable implementation of IC will be difficult to achieve unless supporting policies, incentives or requirements are in place.

Adopting and adapting IC is not necessarily easy or intuitive. There are myriad factors that could impact and shape the development of IC in a given urban region. This report attempts to be a starting point to identify potential IC solutions and approaches from a multidisciplinary vantage point. Considerations are given to technical, organizational, economic, regulatory, political, and developmental solutions.

Modern cities have pressing challenges. Though many of which are directly influenced by the function of the building industry — particularly addressing housing demand and minimizing environmental impact — innovation in construction is only one piece of potential solutions. With this in mind, sensible adoption of IC practices can help in achieving some of the goals listed but does little on its own. It rests on collaboration between industry and government experts to make sure the transition towards a sustainable built environment is sensible and inclusive.

This report serves as an attempt to document the intricate ecosystem and enable local stakeholders to make informed decisions about the optimal path to IC adoption in their respective contexts.
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