Past and Present

Contrary to general perception, off-site construction is not a new technology. Throughout history, as far back as circa AD 43, evidence of prefabricated building elements has been found, among the Romans who applied this construction method to build forts quickly and efficiently to progress their conquering campaign. We then fast-forward to the second Industrial Revolution in the late 1800s, and witness the advent of machinery in manufacturing, and the introduction of steel as a construction material. Structural-steel mass prefabrication was carried out in a factory environment, and in some instances, shipped across continents. Since then, not much has changed until recently, when prefabrication has again become the current “buzzword” in our industry, even to the extent of being coined a “Modern Method of Construction.” Why the resurrected interest? Why now? And what next? This paper explores these questions by reviewing critical current trends and describing evidence-based scenarios for the industry. It provides a trajectory for the future of systemization design and construction that is framed around three critical trend certainties: (1) finite natural resources, (2) generation skills shift, and (3) exponential technology growth. These narratives provide a trajectory of what could happen beyond Industry 4.0.

A Finite World

As the world continues to generate waste and deplete itself of natural resources at an alarming rate, the younger generations are calling for serious actions to save the planet. In response, the United Nations formulated an action plan: “Transforming our World: 2030 Agenda for Sustainable Development” in 2015, which provides a shared blueprint
for peace and prosperity for both people and the planet, now and into the future. At its heart are the 17 Sustainable Development Goals (SDGs), which are urgent calls for action by all countries in a global partnership to tackle climate change and work to preserve our natural environment. The following identified SDGs are closely related to the construction space:

• Sustainable Development Goal 9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation.
• Sustainable Development Goal 11. Make cities and human settlements inclusive, safe, resilient, and sustainable.
• Sustainable Development Goal 12. Ensure sustainable consumption and production patterns.

It is recognized that buildings consume a large amount of resources both in energy and material, including significant amounts of non-renewable resources, throughout their life cycle (Jaillon & Poon 2013). The construction activities themselves have significant negative impacts on the environment, such as pollution and waste generation. There is also a recent explosion in product innovations to facilitate renewable energy generation. Although renewable energy is considered sustainable during a building’s operational life, these solutions are short-sighted, and will not achieve their full potential if they are developed and delivered in silos, without consideration of end-of-life treatment.

In order to achieve the targeted sustainability goals, the building industry has a significant role to play, given that it is, after all, a US$1.1 trillion industry in just the United States and Europe, based on statistics provided by McKinsey (Bertram et al. 2019). The construction industry has finally come to a collective recognition that prefabrication is one of the most effective construction methodologies, one that has a potential savings contribution of US$22 billion in these two markets alone (see Table 1). This savings is significant, since it also equates and contributes to the potential value in quantifiable waste reduction.

Prefabication methodology in essence facilitates minimizing waste by designing out construction and operational inefficiencies, including those that extend beyond the material lifespan. Life-cycle design incorporates prefabrication disassembly and deconstruction to maximize the reuse and recycling of building components as well as materials, in order to achieve a circular economy.

Jobs for Tomorrow

In comparison to other industries, the construction industry has historically been heavily reliant on workers who are skilled in manual labor. However, as construction volume increases due to population growth, this reliance is no longer sustainable or resilient for the industry (see Figure 1). With an increasing aging of the current workforce, including more stringent safety and health

---

Table 1. Modular construction in Europe and the United States with up to $22 billion potential savings. Source: Bertram, et al. (2019)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Repeatability</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Unit Size</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Value Density</td>
</tr>
<tr>
<td>Single Family</td>
<td>376</td>
<td></td>
<td>30</td>
<td></td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multi Family</td>
<td>277</td>
<td></td>
<td>45</td>
<td></td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Office Buildings</td>
<td>77</td>
<td></td>
<td>10</td>
<td></td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hotels</td>
<td>40</td>
<td></td>
<td>10</td>
<td></td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Retail</td>
<td>42</td>
<td></td>
<td>5</td>
<td></td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Logistics / Warehouse</td>
<td>46</td>
<td></td>
<td>10</td>
<td></td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Schools</td>
<td>59</td>
<td></td>
<td>15</td>
<td></td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hospitals</td>
<td>41</td>
<td></td>
<td>5</td>
<td></td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other Buildings</td>
<td>70</td>
<td></td>
<td>5</td>
<td></td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Buildings Total</td>
<td>1,027</td>
<td></td>
<td>135</td>
<td></td>
<td>22</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1 European countries included: Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Hungary, Ireland, Italy, Netherlands, Norway, Poland, Portugal, Slovakia, Spain, Sweden, Switzerland & United Kingdom.
2 Includes only new building projects. Renovation/maintenance projects are less suitable for modular construction, but offer other productivity gain potential.
3 Informed estimates. A full moon corresponds to a potential construction project value for (additional) modular construction of ~30%, a quarter moon thus to ~7.5%, in 2030.
4 Informed estimates. A full moon corresponds to savings potential of ~20%, a quarter moon thus to ~5%, for each € of addressed construction expenditure.
5 No unique layout requirements (either from regulation, or design expectations).
6 Small unit size allows standard transportation.
7 High complexity of units, high share of wet rooms, etc.
8 Used 2017 average annual exchange rate to convert to $ from Euroconstruct data in €.
regulations for older workers, in order to perform physically demanding tasks, as well as a fundamental shift in the upcoming generation skills set, the construction work typology is set for a steep change over the coming years. Without a doubt, today’s jobs will not be the same jobs tomorrow.

Several studies have suggested advanced technologies could automate up to 75 percent of jobs in the coming decades (Quezada et al. 2016). Smart machines that accomplish routine tasks, such as tiling and bricklaying, are likely to be a fixture of the industry within a decade, replacing manual skills. New competencies and jobs will emerge, and others will fall away. The advent of a tech-savvy generation with an innovation-focused mindset and creative complementary skills in manipulating machinery and technology will be the essence of a new remote workforce, as opposed to a traditional, site-specific physical labor presence.

The very nature of prefabrication methodology lends itself to complement this shift in paradigm, focusing on structured process automation performed in a safe and controlled environment, at greater speed and with greater quality and precision.

The Technology Explosion

There is no denying that the world today is experiencing the rise of a new technological era, commonly known as Industry 4.0, essentially a subset of a wider fourth Industrial Revolution, which is trending towards the design, construction and maintenance of smart cities. Industry 4.0 in construction leverages the advancement from automation and data exchange in both manufacturing technologies and processes, which include: cyber-physical systems (CPS), the Internet of Things (IoT), common database and cloud computing, and cognitive computing with AI and deep machine learning (ML).

Technology-driven cross-transference, within niche pockets of the prefabrication space, is being realized in the building industry. This is currently seen among technological giants such as Google and Amazon, which are advocating and funding digital smart features into their built spaces as a baseline. The design-build concern Katerra is an example of an extreme disruptor to the present construction industry. Its approach is a full vertical integration from end to end, and will be centered on an “Industry 4.0” smart factory prefabricating building products. The factory includes machinery augmented with wireless connectivity sensors, system visualization of the entire production line, and to a certain extent, autonomous decision-making. The success of this venture is still to be fully tested, but it clearly demonstrates the direction and scenario of things to come (see Figure 2).

Developments and breakthroughs within the biosciences and materials science industries, especially in nanotechnology, provide application opportunities for innovative building products to create smart living buildings and smart cities that are both integrated and resilient.

Systemization and Beyond

Based on the current narrative, driven by social, cultural and technological transformation, it is inevitable that the projected construction landscape will be vastly different from what we know now. The societal multilevel perspective can be applied and categorized in three main conceptual patterns of transformation (Geels 2002).
Firstly, the global recognition of climate change challenges will redefine cultural behavior based on a population-conscious generation demanding sustainable products and a sustainable built environment. With collective demand, the industry is propelled to respond, capitalizing on the current technology of Industry 4.0 and forming the first wave of transformation.

The second concept pattern is rapid urbanization, fused with the general acceptance that buildings can no longer be perceived as bespoke structures. Instead, buildings will be perceived as mass customizations of integrated, systemized products that are designed for automation, deconstruction and recyclability. Aesthetic uniqueness will not be compromised, but can still be achieved with mass customization, through the creative adaptive envelope via material nanoscience.

The final behavior pattern is driven through external factors and trends of gadgetry-immersive interactivity, which exerts influence on societal conjecture, driving the expectation of living in a fully-responsive built environment within spaces designed to biophilic standards.

As demonstrated by the COVID-19 pandemic, with sufficient landscape and regime pressures, social behavior transformation can be almost immediate and irreversible: such as the acceptance of the “new normal” of working from home. However, with this change comes further reliance on technology and the associated expectation of instantaneous connectivity and integration in a multi-functional “home space” and infrastructure.

In response to these current societal transformations, the shift in the construction landscape of tomorrow can be described from various perspectives. Regardless of how this is being viewed, it is essentially anchored around the concept of systemization to provide sustained resilience and adaptability. As illustrated in Figure 3, there are five areas to achieve a complete holistic systemization process where the methodology is intimately interrelated: design, manufacturing, construction, function, and regeneration.

Design
The first step in systemization design is an overhaul of the traditional design thinking from an “outside-in” to an “inside-out” approach. Building components are broken down and oriented into objects with commonality classifications, in a technique known as Kit-of-Parts (KoP). The base geometry of the parts is governed by parameters such as structural integrity, parts interconnectivity, and manufacturing and logistical constraints; the design of which is further refined with parametric modeling to achieve maximum efficiency.

The next design phase is integrated layering, where building services and finishes are applied to the base parts. However, it is paramount that the design incorporates a
reversal process to facilitate layer segregation, in order to accommodate end-of-life reuse and facilitate reincarnation capability (see Figure 4).

In addition, through deep machine learning (DML) application, optimization of systemized KoP as building blocks to generate site-specific building configurations can be achieved before the systemized design data is translated across for manufacturing. The success of DML application is reliant on a shared global big-data platform to maximize accuracy and facilitate intelligent decisions making by an "artificial neural network."

Manufacturing
Common data exchange platforms allow design information to be communicated to computer numerical control (CNC) routers, for autonomous tasks to be performed by AI in a smart production facility. The application of sophisticated CPS that combine physical machines and business processes facilitate cyber-cognition as a form of DML. This renders the process self-diagnostic, self-configuring, and self-resilient, to ensure quality systemized product whilst maintaining a lean production line.

The interconnectivity within and outside the smart facility is provided and supported by IoT, an example of which is the data tracking of raw materials from the base source through to the final assembled product, and throughout its lifespan. Another IoT application is sensing technology on self-driving vehicles (SDVs) used for material handling to improve efficiency and safety as systemized products are being transported.

Additionally, blockchain technology is utilized to facilitate financial transactions of materials and services throughout the process, contributing the transparency and traceability of a shared ledger within a distributed network. The blockchain technology allocation is not only limited to financial transactions, but also provides a single common platform, allowing for the most efficient transmission of stored information.

Construction
Unmanned aerial vehicle (UAV) or "drone" technology is used to transport systemized products from the smart factory located close to the actual site. Predictive studies have indicated that as early as 2036, the sky could be teeming with industrial drones. Smaller and more intricate parts are 3-D-printed with sustainable composite material in this temporary localized production area. DML is utilized to sequence the construction process with just-in-time (JIT) delivery and installation. The procedure mapping by DML is tested against the digital twin, an exact replication of a physical object.
in a virtual format, prior to actual site assembly. The powerful processing capabilities of the digital twin are intended to provide monitoring insights on product or system performance, complete with pre-emptive consequences in the real physical world (see Figure 5).

Based on the above, on-site handling will be limited to overseeing robotics systems, examining data feeds and AI programming. It is anticipated that all heavy lifting will be carried out by agile robotic labor. The personnel operating the machines can be based miles from the assembly sites, but with the support of real-time IoT connectivity, they can still provide adequate on-site support.

Function
The completed systemized infrastructure will function as a "living habitat," which is modeled on the concept of biomimicry, in which nature always operates on the principles of economy and efficiency while generating no waste, balancing the way the planet’s resources are used. The systemized products work collectively to generate a reactive, responsive and restorative smart space.

Sensor-embedded probes within the systemized elements collect and process real-time data on the performance of the habitat, which then self-regulates the parameters for continuous optimization. Sensing technology is not just limited to environmental quality, such as heating and cooling and carbon-dioxide content in the atmosphere, but also can detect cues from the inhabitants of the space and subsequently respond accordingly.

As a basic example, with nanotechnology applied to a systemized wall, the color of a room can be calibrated in response to the psychological needs of the inhabitants. While the internal building responds to the occupants, the external envelope reacts to the environment in a naturalized fashion. Biomimicry technology is not limited to adopting nature’s geometry only, as illustrated in Figure 6, it can also be applied to building performance. Figure 7 shows an image of the extraordinary BIQ “algae house” Building in Hamburg, constructed in 2013, which incorporates living microalgae into its design, known as a “bioreactor façade.” The algae control light entering the building and provide shade when needed. When enough algae have grown, they are harvested and used to make biogas (a renewable energy source made from raw materials) to supply

“On-site handling will be limited to overseeing robotics systems, examining data feeds and AI programming. It is anticipated that all heavy lifting will be carried out by agile robotic labor.”
the building. Currently a “bespoke” one-off construction, this type of component could one day soon be systemized and mass-produced.

As demonstrated, there is a huge potential for future mimicry applications. One of the latest research possibilities is for the façade to behave like “bionic leaves” that perform photosynthesis using a combination of water, sunlight and carbon dioxide to transform into energy and oxygen, which is then used to service the building (Reuell 2016). Parts of the sensitized, systemized building blocks are also automated with adaptive movement capabilities, in reaction to the climate.

The collective data that loops across the systemized product forms the lifeline feeding into a centralized processing platform for self-diagnostic problem-solving, generating a return transmission of restorative adjustment and ensuring a continuous functional, reactive living habitat.

**Regeneration**

Through ongoing and constant building health monitoring via self-sensing materials, end-of-life or defective products are identified in a timely manner, and have been designed for easy replacement. Localized disassembly and dismantling of entire buildings will be accommodated through mechanically-reversible interlocking parts. The condition of the dismantled, systemized KoP is intelligently assessed for further reuse, repurposing or recycling, instead of heading straight to the landfill (see Figure 8).

The designed KoP allows for the systemized layers to be stripped and updated with new technology, while reusing the base frame. Removed layers can be recycled for alternative use, minimizing wastage and maintaining the circular economy cycle (Peaks & Brandmayr 2019).

**Timeline Projection**

The transformation landscape has begun, and is anticipated to grow in scale in the coming decades. However, with the additional pressures from the COVID-19 pandemic, it is highly likely that the impending changes will be further accelerated. Based on a survey carried out by McKinsey in June 2020, it was reported that 80 percent of respondents believe that the construction industry will look radically different in 20 years (Pinner, Rogers & Samandari 2020). The initial accelerated transformation will correspond to technologies that facilitate remote working; data interconnectivity, accessibility and visualization, such as IoT technologies with product-based design and added-value manufacturing, with automated machines and AI in construction.

The unprecedented global pandemic disrupted daily industrial activities and provided nature a chance to reverse the effects of years of environmental abuse; providing evidence of the reality of climate change and a vision of an alternative, cleaner world that would be a catalyst of change to current sustainable strategies. There is no better time than the present for sustainability-related green technological

“Localized disassembly of entire buildings will be accommodated through mechanically-reversible interlocking parts.”

---

---

Figure 8. Minimum waste end of life regeneration to maintain a circular economy. Source: Peter Strong Interior Design (2014)
investments, especially since it is anticipated that most countries post-COVID-19 will be regenerating their economies at least partly through publicly-funded construction projects. This represents an opportunity for re-evaluation and redirection, creating economic and environmental resiliency for the future.

In parallel, the advancement in bio- and nanoscience technologies will eventuate into a cross-transference application, as discussed in previous sections. Figure 9 illustrates the timeline convergence of the collective key technologies sectors into the systemized built environment. The trajectory indicates that this could possibly occur as soon as 15 to 20 years from now.

Conclusion

The landscape pressures on the current construction industry are converging to a singularity that demands an effective, sustainable and resilient response. Prefabrication, in its basic definition, has been around for a long time. However, now, together with the application of Industry 4.0 technologies, it is finally set to leap forward, in the shape of systemization as a serious responder and disruptor. The explorative narrative described in this paper may take time to be fully realized, and will no doubt be fraught with challenges along the way. Despite this, from current evidence-based scenarios within the industry, systemized prefabrication supported by technology is trending in the right trajectory. It is important to appreciate that the entire systemized process is intertwined; design, manufacturing, construction, operation and regeneration. This narrative, although focused on the life cycle of one systemized building, is scalable to create an entire integrated smart city. For this vision to be realized, industry, government, and academic collaboration will be required to engineer the basic building blocks for resiliency beyond tomorrow. Success relies on a holistic approach, underpinned by a common goal for a more sustainable future.

Unless otherwise noted, all image credits in this paper are to the author.

References


